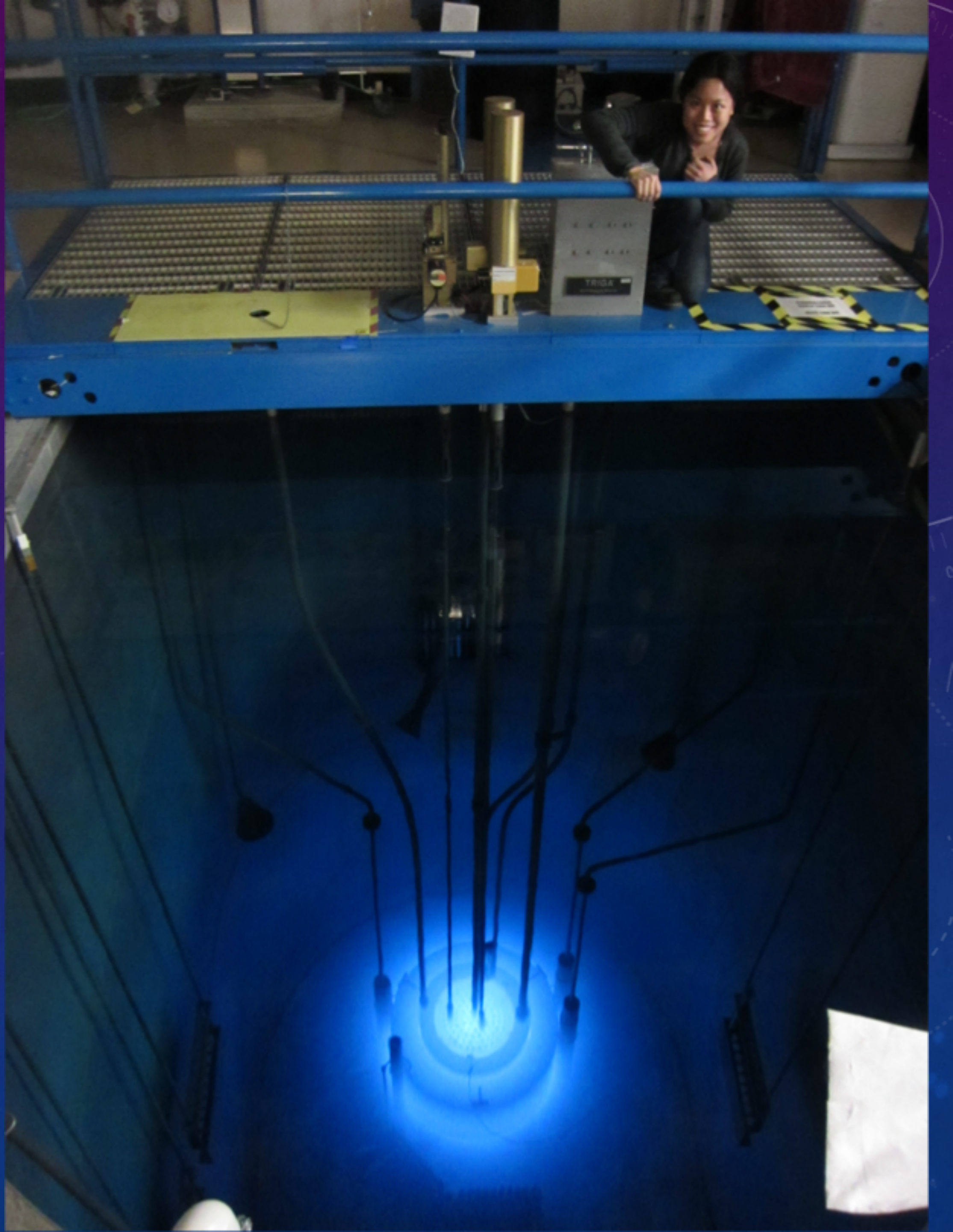
INTRODUCTION TO ACCELERATORS

CINDY JOE

JUNE 4, 2020

ABOUT ME

- Bachelor's in Physics from Reed College in Portland, Oregon; nuclear reactor operator
- Fermilab since 2010
  - **Today is the 10th anniversary of my first day at Fermilab 🎉**
- Most of that time: particle accelerator operator
- I like big science machines!
- Currently an engineering physicist: *I solve problems!*
- Work with neutrino experiments and manage the NuMI Underground experimental areas at Fermilab



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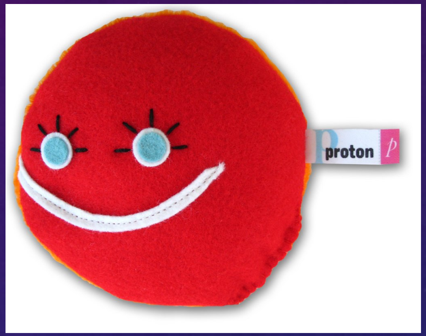
MORE INFORMATION

- This is partly adapted from a 2 hour lecture I give high school students in Fermilab's Saturday Morning Physics program
- I will keep things quite general conceptually, so we can cover a lot of diverse ground in a short period of time. I will focus strongly on operational aspects because of my own experience
- There are a great deal of further topics in accelerator physics in particular to explore
  - USPAS: https://uspas.fnal.gov
  - Talks by prior/other speakers, particularly for this lecture series, Saturday Morning Physics, USPAS intro course, and others. Especially **Adam Watts**, Eric Prebys, Bill Barletta
  - Fermilab Accelerator Operations "Rookie Books": https://operations.fnal.gov/rookie_books/rbooks.html In particular, "Concepts"
- **My email: cindyjoe@fnal.gov**

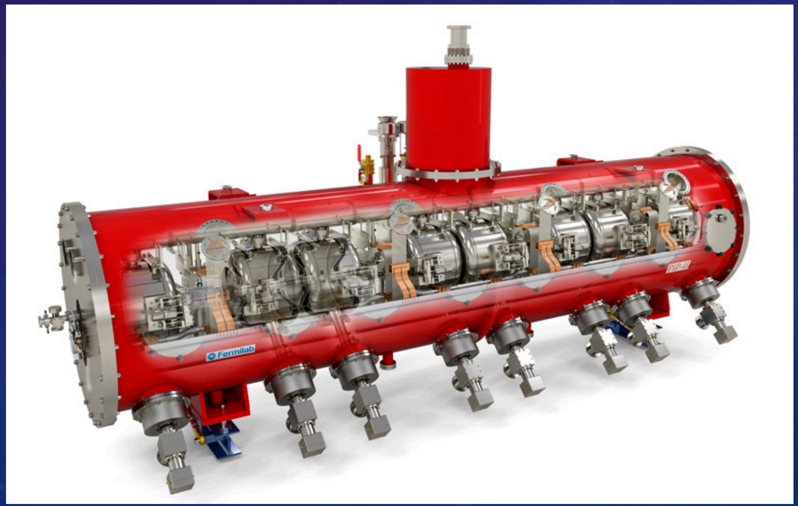
MOTIVATION

WHAT IS A PARTICLE ACCELERATOR?

- PARTICLE: subatomic particles (usually; can also use ions)
- ACCELERATOR: makes a particle go faster = gives it extra energy
- So a particle accelerator is a machine that we use to add energy to particles of matter

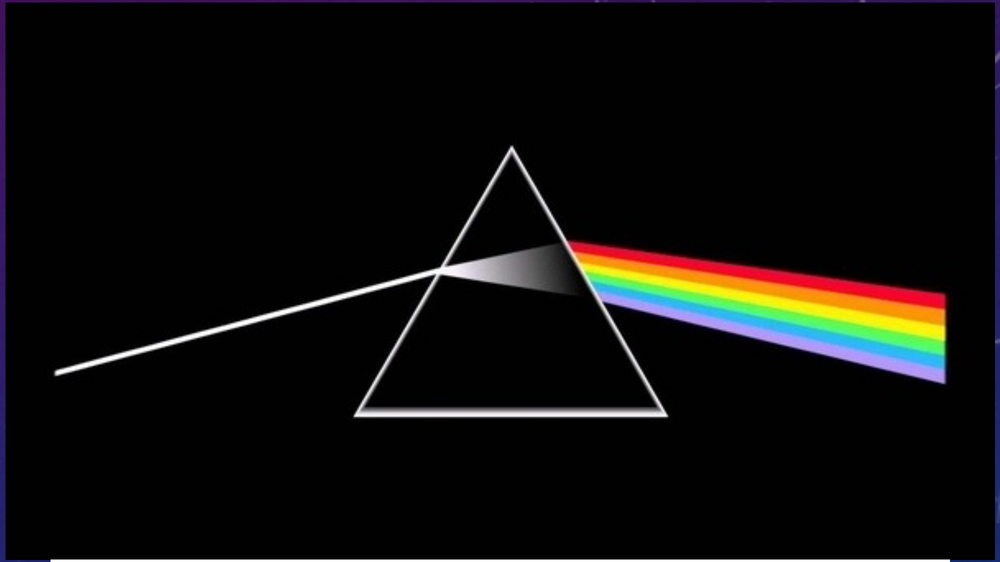


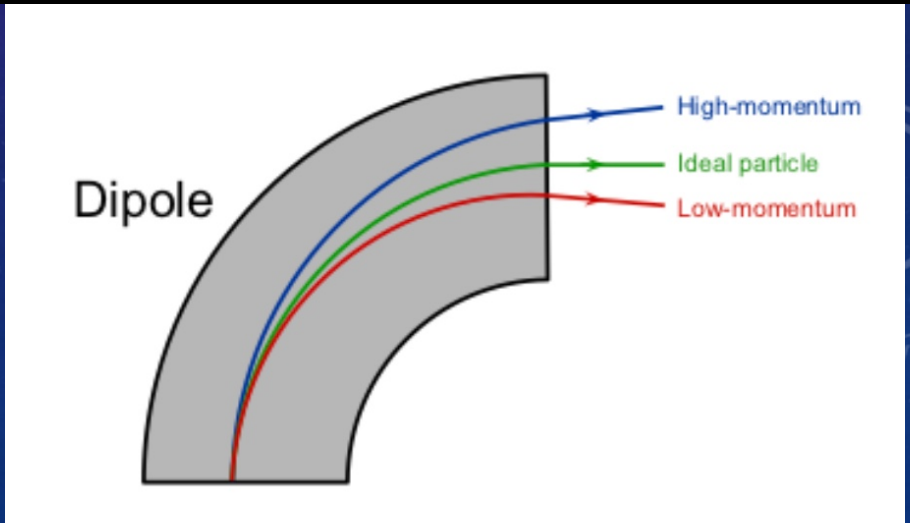




TERMINOLOGY: BEAM

- We typically consider not one single particle, but how a whole collection of them behaves on average
- Analogy to a beam of light, which may be refracted, focused, bunched, and otherwise manipulated in its travel



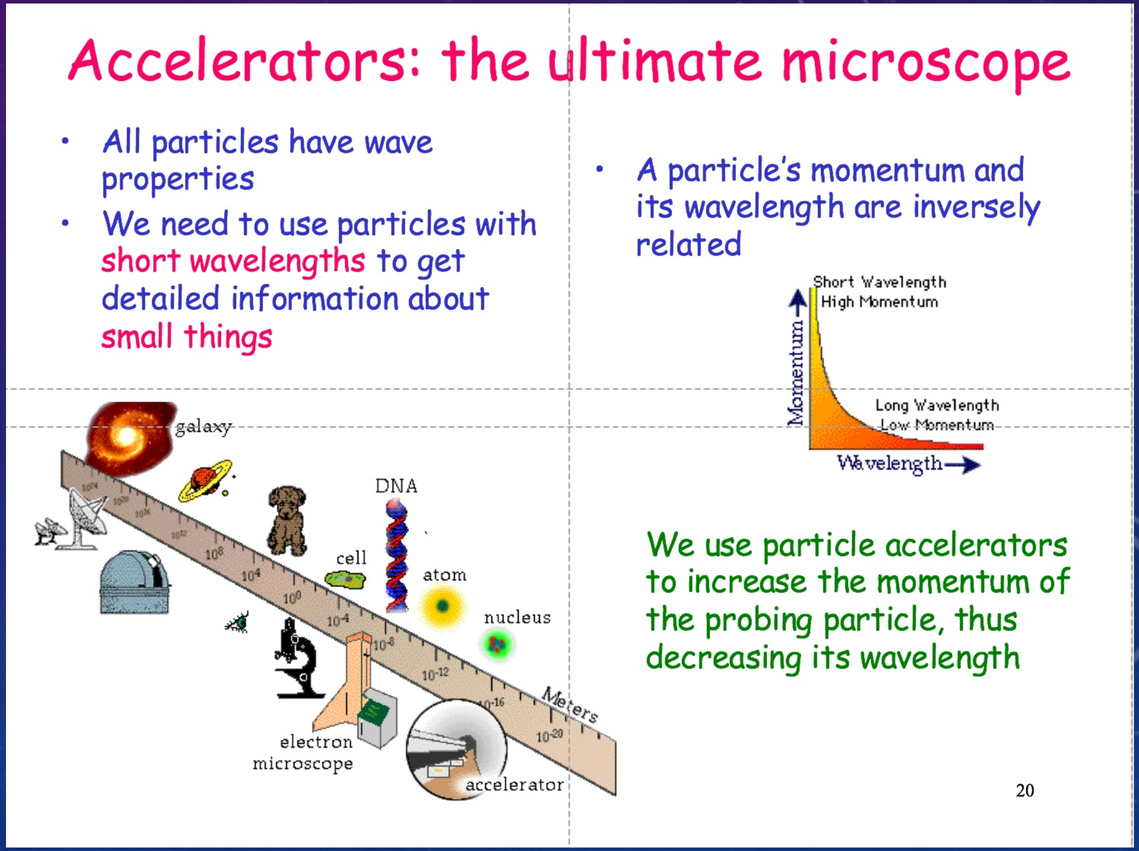


WHY DO WE ACCELERATE PARTICLES?

- Materials science, medicine, research: there are many uses
- You can look up more at http://www.accelerators-for-society.org
- I will concentrate on what we do here at Fermilab: high energy particle physics

PARTICLE ACCELERATORS ARE OUR EYES

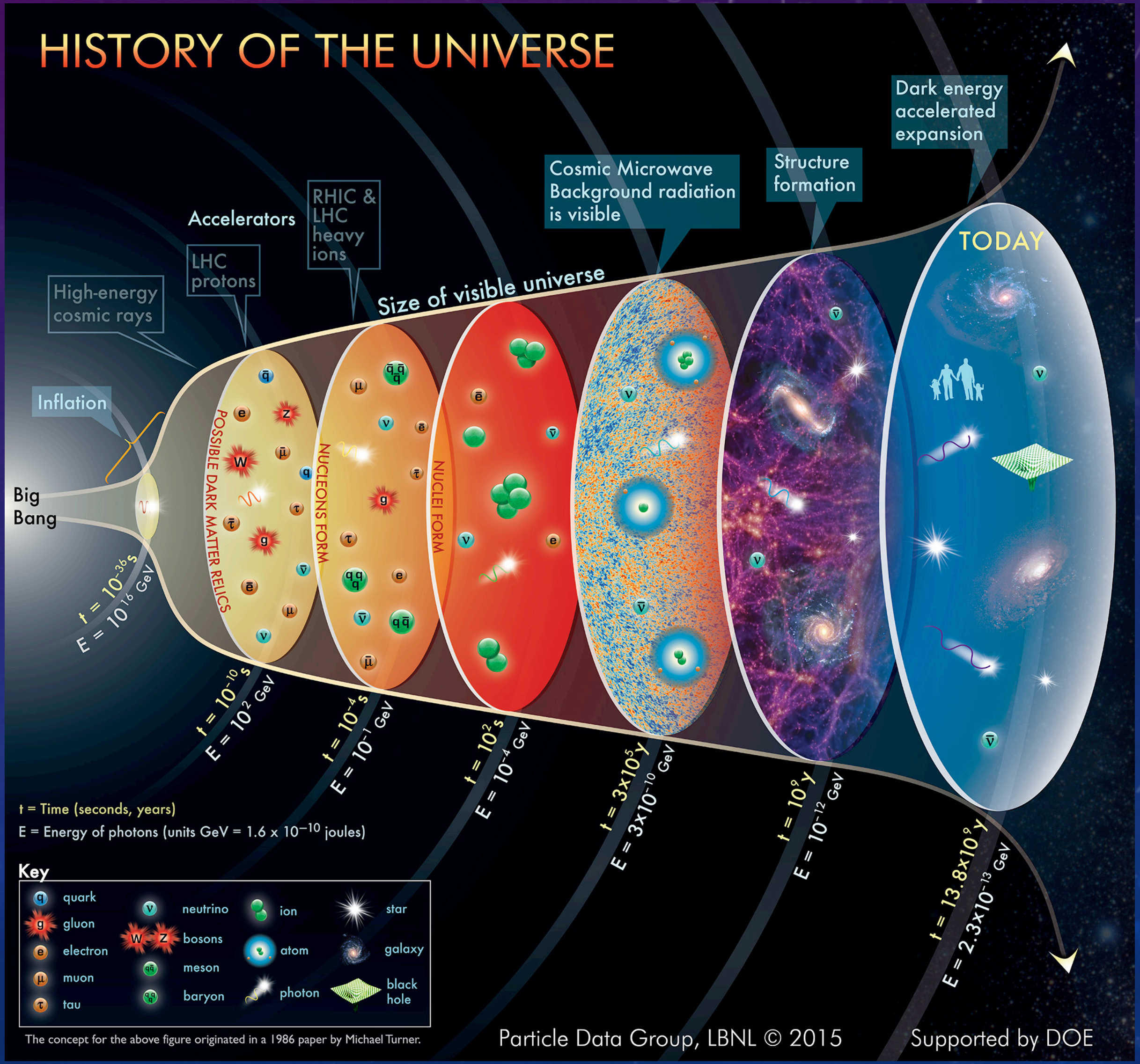
- Particle accelerators (and detectors) are the tools of high energy physics
- $\lambda = \frac{h}{p}$



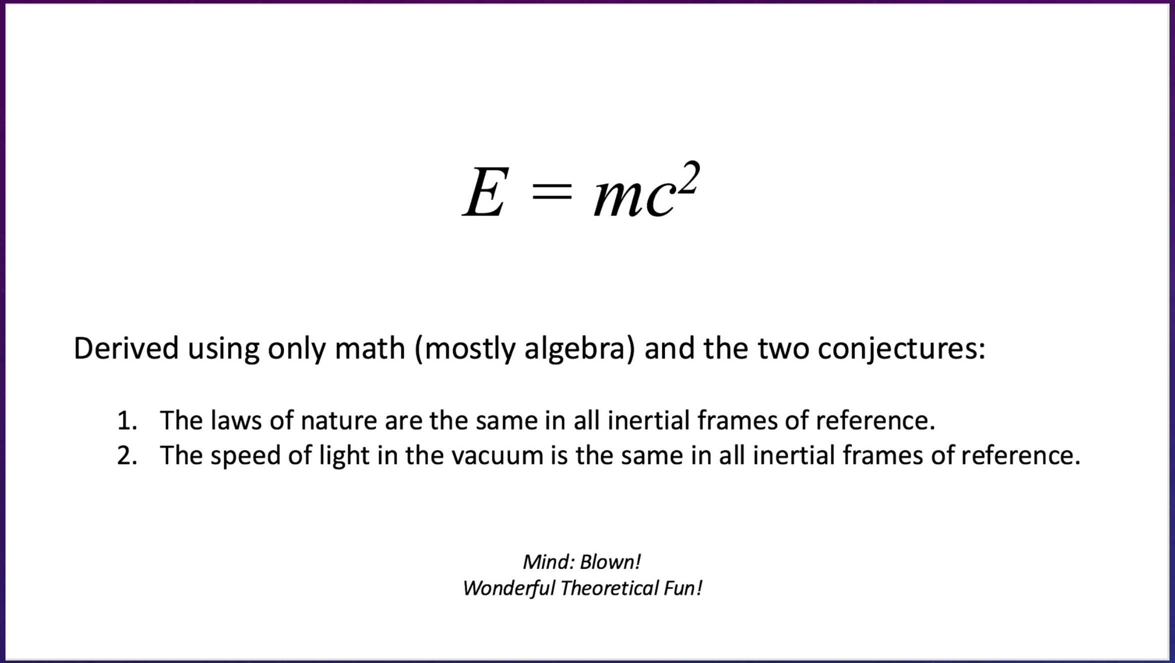
From Cecelia Gerber's Saturday Morning Physics talk

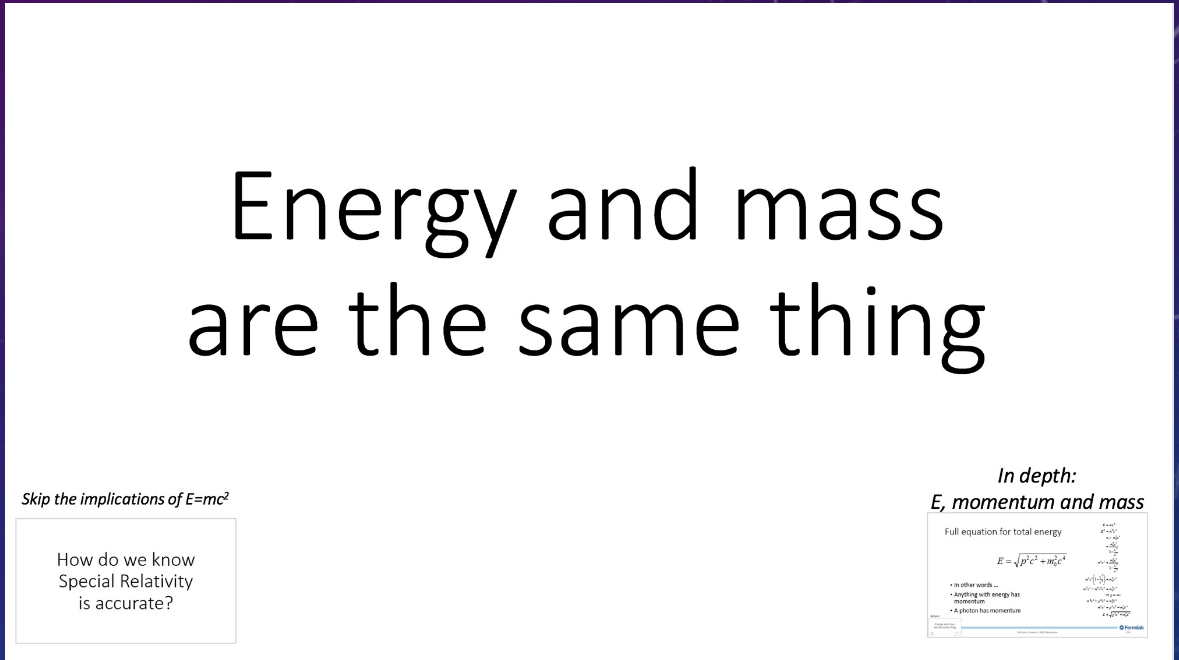
ACCELERATORS LET US GO BACK IN TIME (!)

- Accelerators let us re-create conditions like those a few *trillionths* of a second right after the Big Bang, 13.8 billion years ago
- This can give us more information about the formation of the universe, the structure of matter, where the universe might be headed



WE CAN CREATE NEW PARTICLES



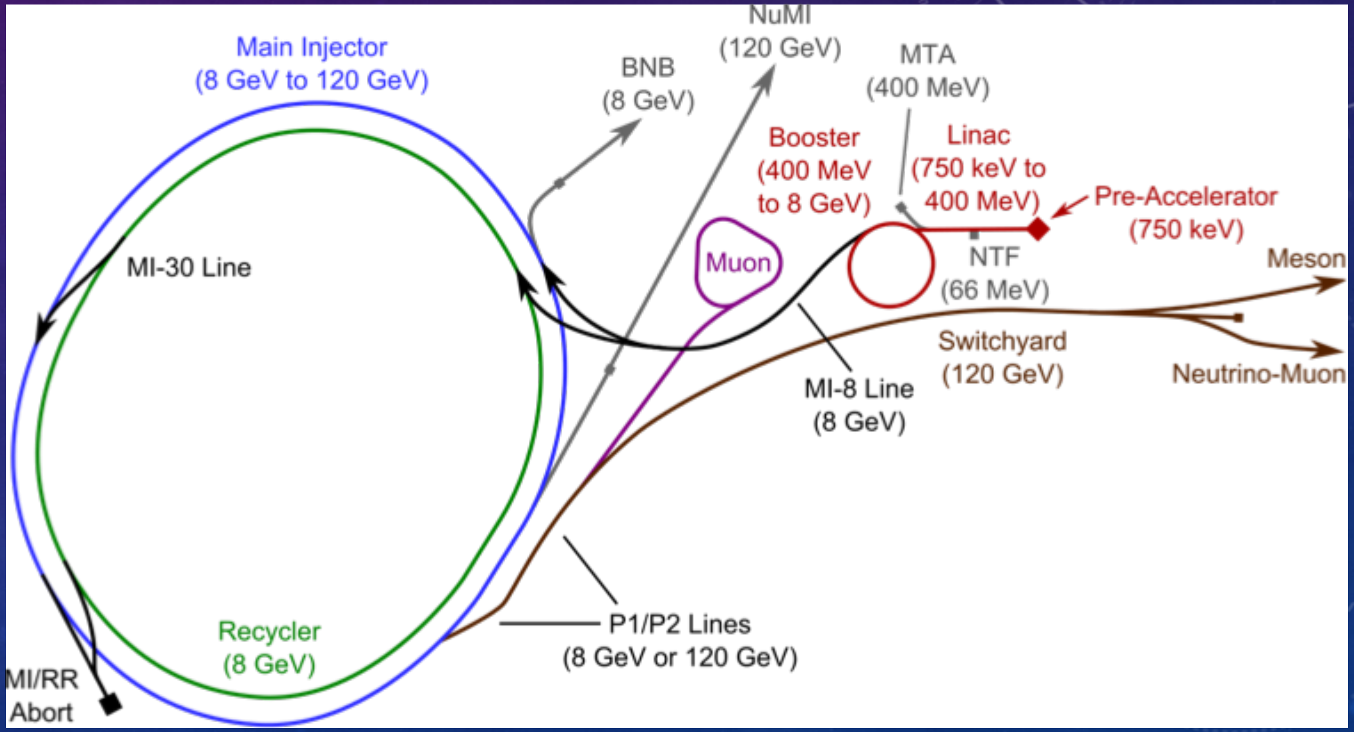


From Elliott McCrory's Saturday Morning Physics talk

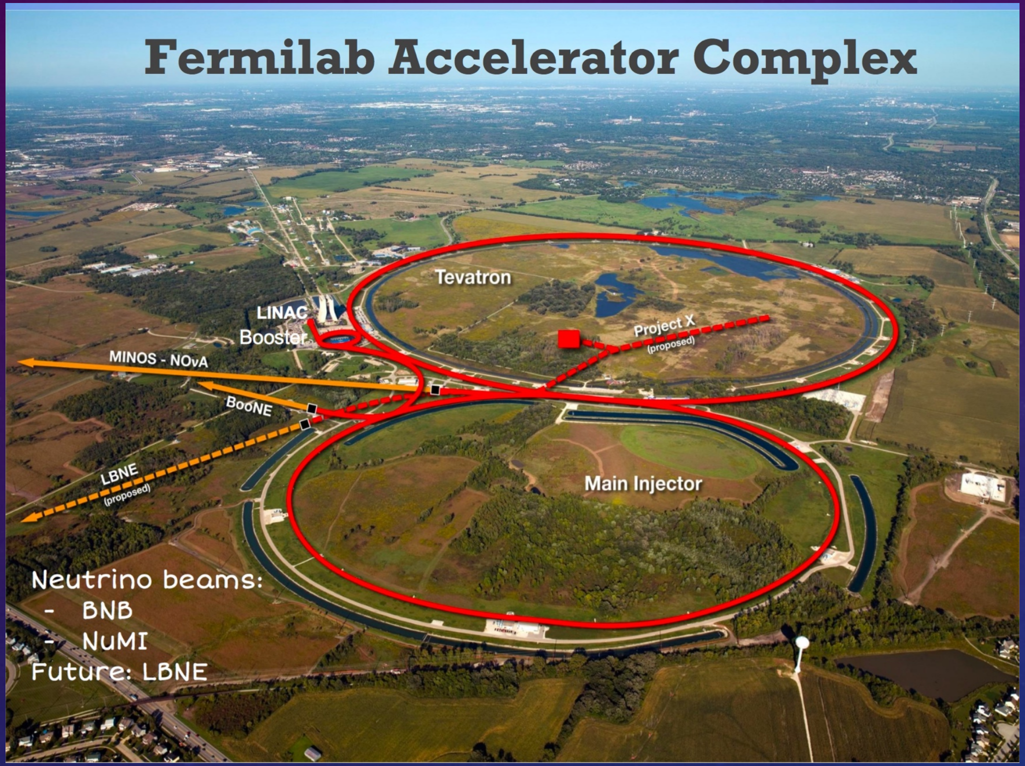
- We are giving particles extra energy, and later we can turn that extra energy into mass = NEW PARTICLES!

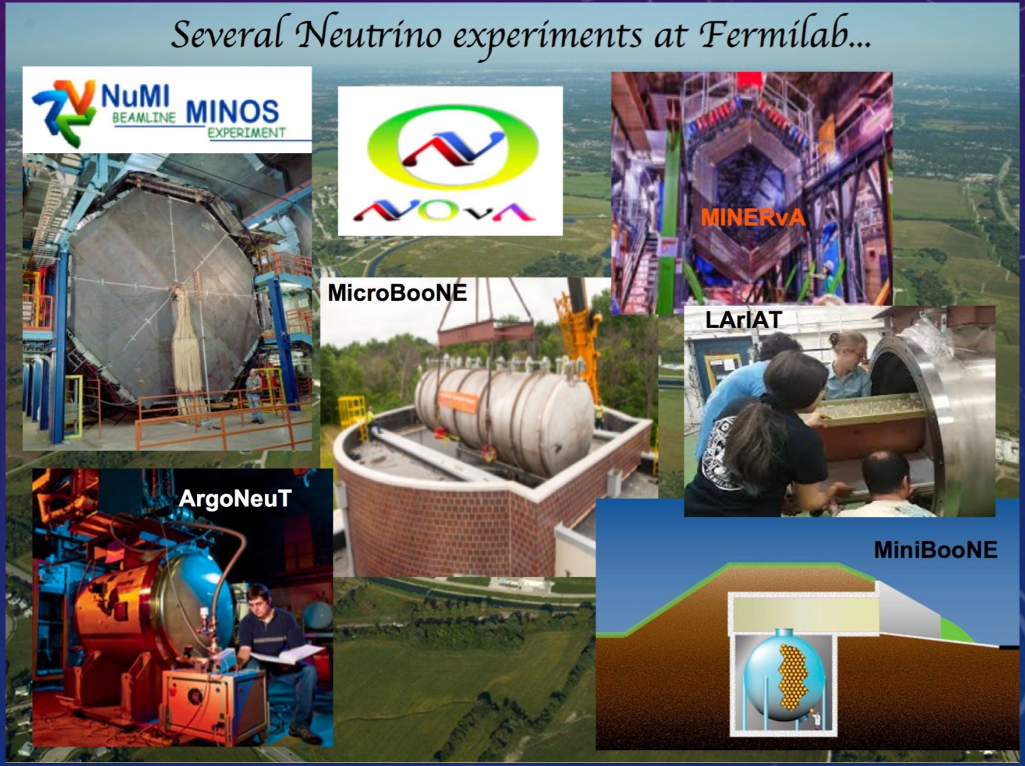
FERMILAB'S SUITE OF PARTICLE ACCELERATORS

- Pre-Acc, or H- Source and RFQ (0 to 750 KeV)
- Linac (750 KeV to 400 MeV)
- Booster (400 MeV to 8 GeV)
- Recycler (8 GeV, RF manipulation and slip-stacking)
- Main Injector (8 GeV to 120 GeV)
- [Historical] Tevatron (150 GeV to 1 TeV)
- [Test] Integrable Optics Test Accelerator (IOTA) at Fermilab Accelerator Science and Technology (FAST) facility
- [Development] PIP-II



ACCELERATORS AND EXPERIMENTS





Both slides from Leo Aliga's Saturday Morning Physics talk

WE HAVE DESIGNED ACCELERATORS TO HELP US EXPLORE WHAT WE WANT TO LEARN

- It is possible to conduct experimental particle research *without* particle accelerators
- For example, in neutrinos: IceCube (high energy cosmic neutrinos), Daya Bay (reactor neutrinos)
- But accelerators allow us an otherwise impossible degree of experimental control. Species of particle, energy, direction, flux, whether it’s on or off at any given time, and many other parameters
- So accelerators play a very important role in the experimental confirmation of the Standard Model, and the exploration of physics beyond it
- Accelerators come with practical limitations, but also a great deal of interesting physics, technology, and engineering in their own right
- Operational mindset

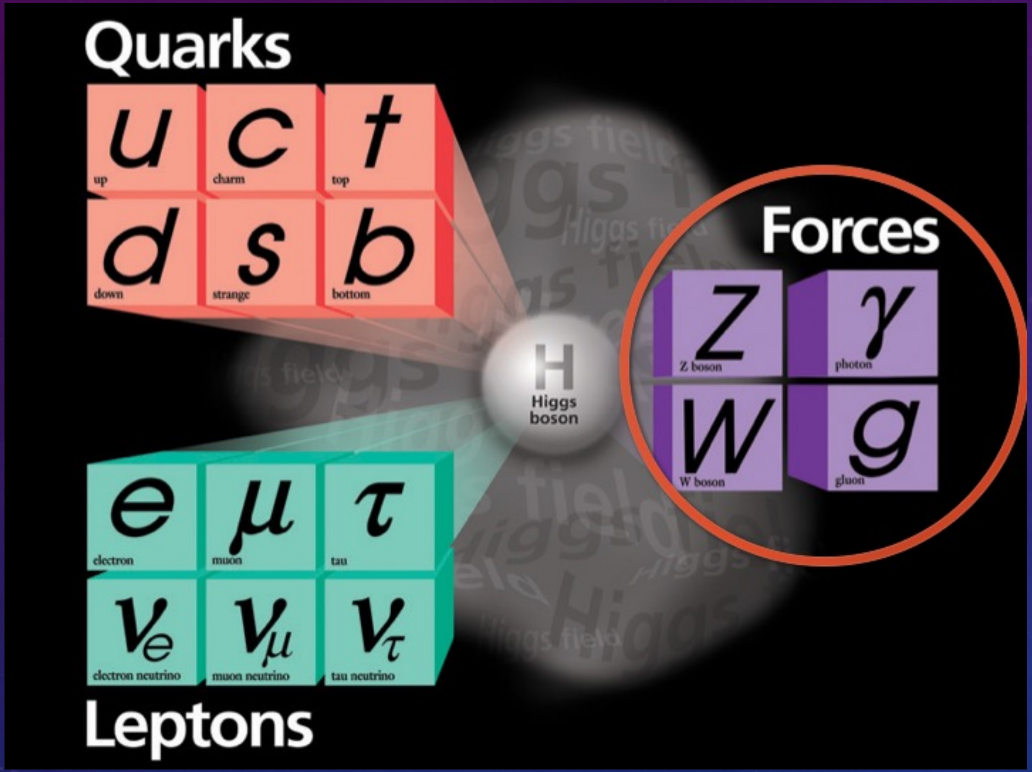
LET’S BUILD A PARTICLE ACCELERATOR

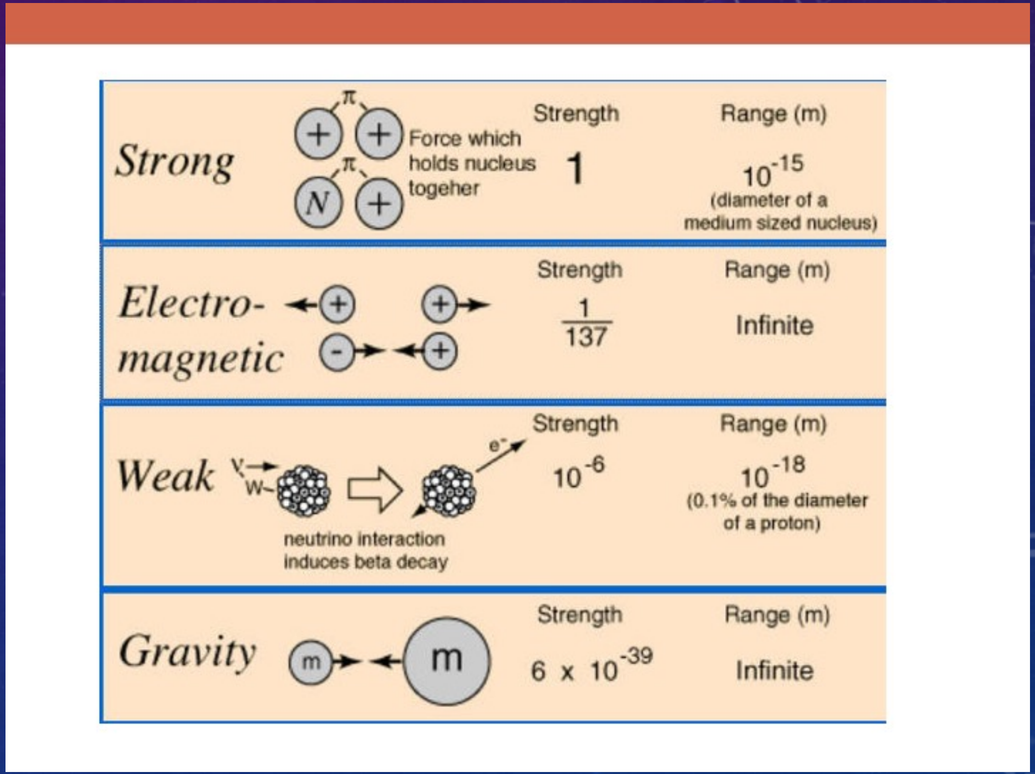
THE CINDYTRON

(you can name yours after yourself)

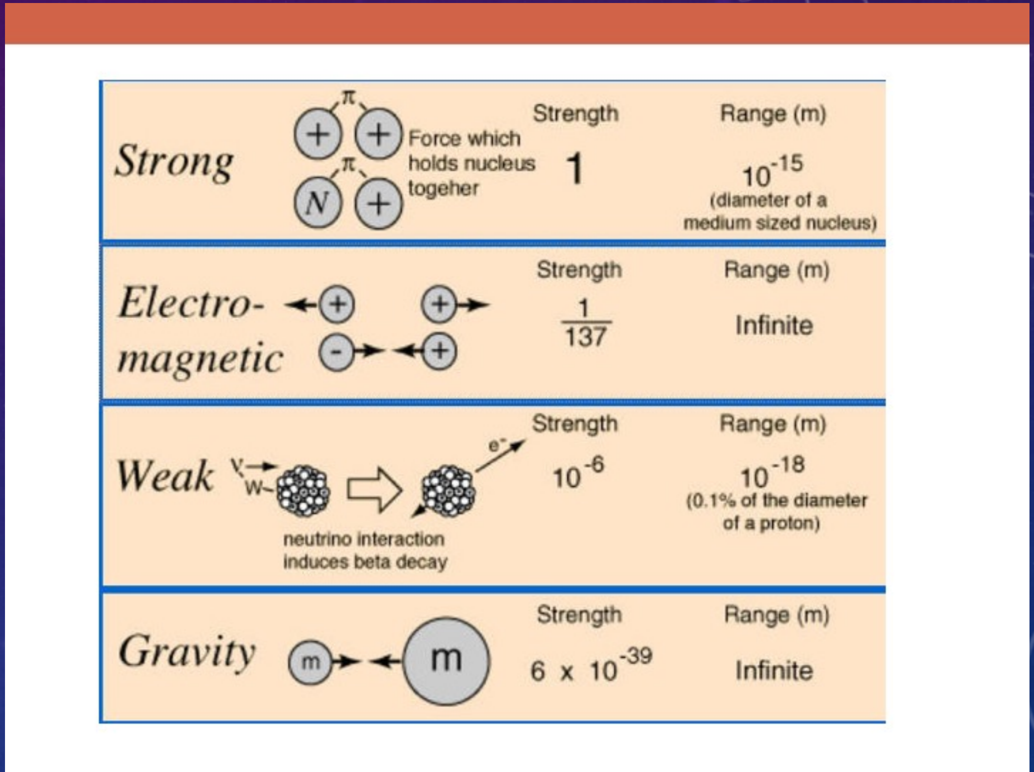
THE CINDYTRON

SO HOW DO WE ACCELERATE PARTICLES?





SO COULD WE USE GRAVITY?

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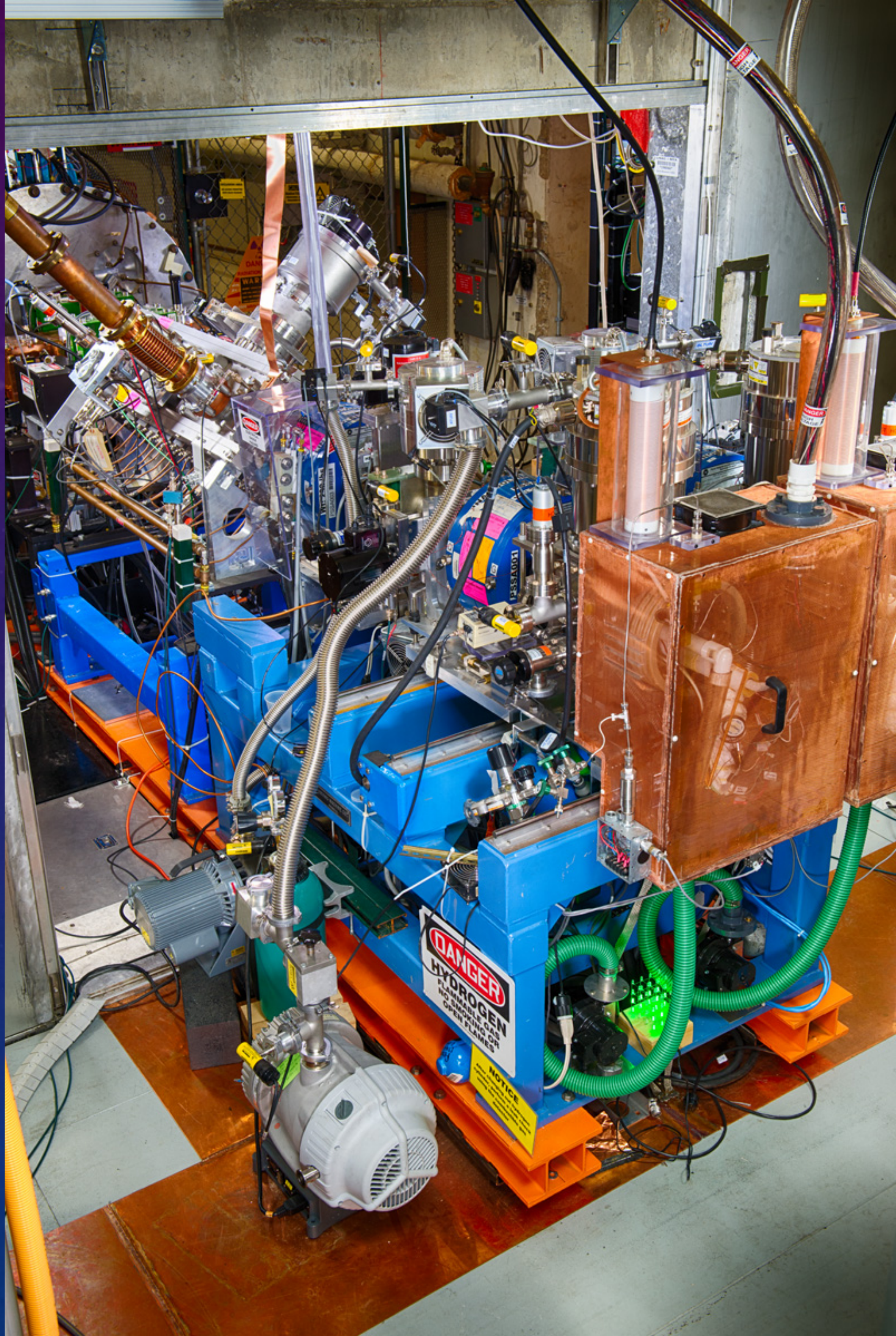
A GRAVITY ACCELERATOR?

- What height would you have to drop an H- ion from for gravity to accelerate it to 750 KeV of energy – the energy and particle which we handle in the Fermilab Pre-Acc?



What height would you have to drop an H- ion (one proton, two electrons) from for gravity to accelerate it to 750 KeV?

$$W = F\,d = F\,\Delta x$$

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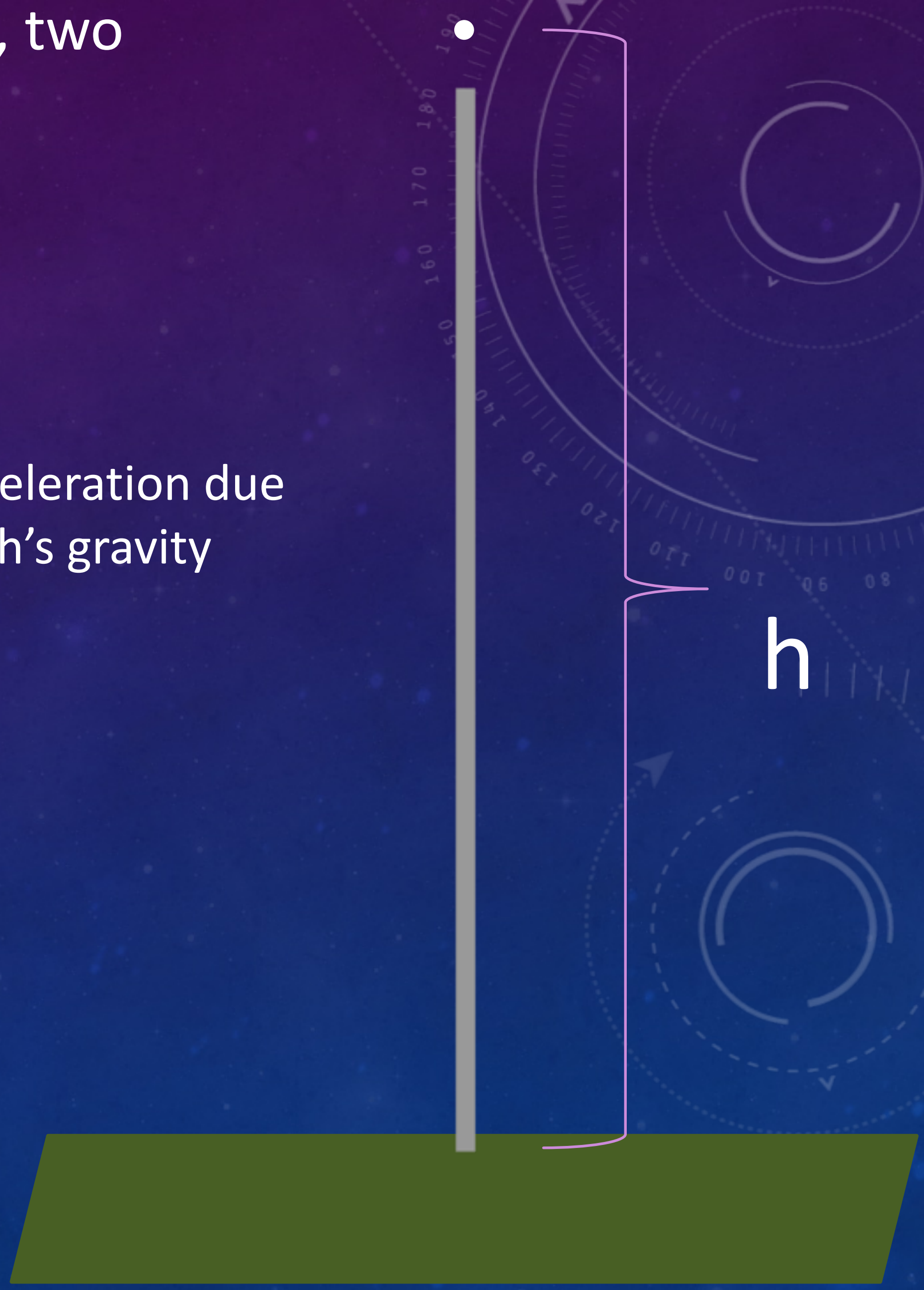
Set:

$W = 750$ KeV,

$F = m\,a = m\,g$

$\Delta x = h$

g = acceleration due to Earth's gravity



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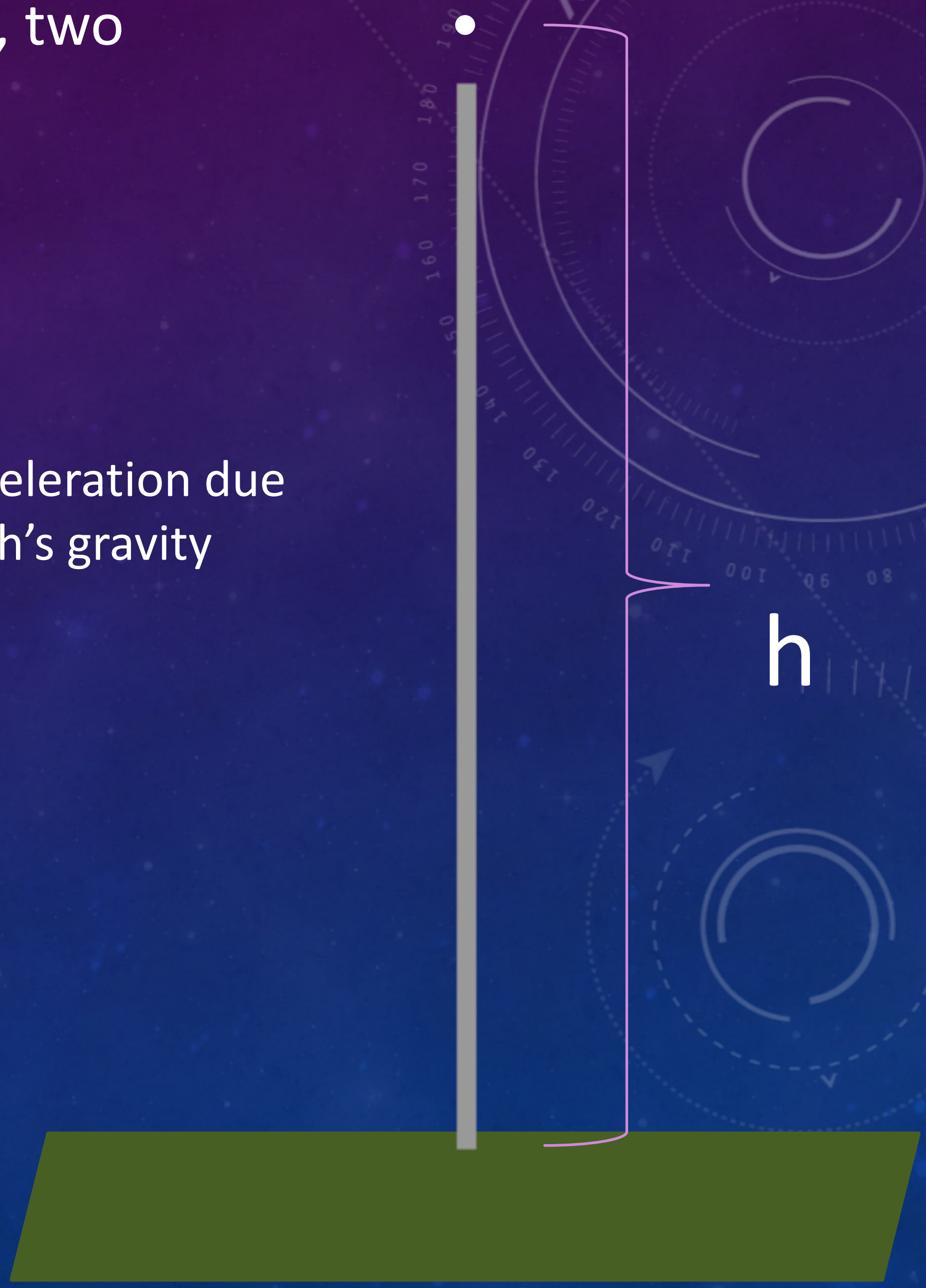

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$W = F\,d = F\,\Delta x$

Set:

W = 750 KeV,

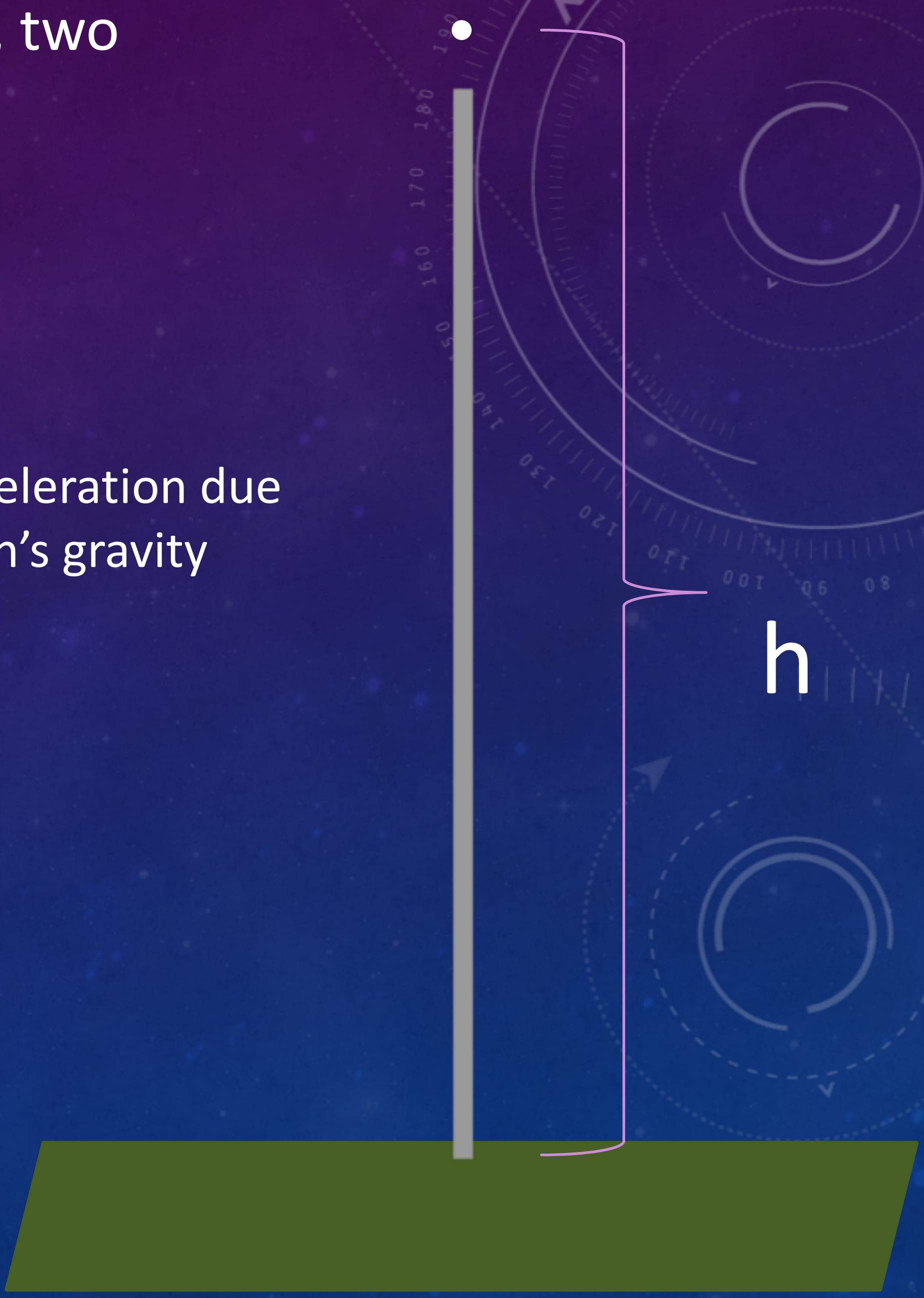
F = m a = m g

$\Delta x = h$

g = acceleration due to Earth's gravity

750 KeV = m g h

Solve for h.



$W = F\,d = F\,\Delta x$

$750\ \text{KeV} = m\,g\,h$

Let’s make some substitutions.

$W = F\,d = F\,\Delta x$

750 KeV = m g h

Let's make some substitutions.

1 eV = 1.602×10^{-19} J, so
750 KeV = 1.204×10^{-13} J

For a H- ion, 1 proton + 2 electrons
m = 1.672×10^{-27} kg + 2 (9.11×10^{-31} kg)
= 1.6738×10^{-27} kg

g = 9.8 m/s^2 (near the Earth's surface)

Plugging it all in…

$W = F\,d = F\,\Delta x$

750 KeV = m g h

1.204×10^{-13} J = 1.6738×10^{-27} kg * 9.8 m/s^2 * h

$W = F\,d = F\,\Delta x$

750 KeV = m g h

1.204×10^{-13} J = 1.6738×10^{-27} kg * 9.8 m/s^2 * h

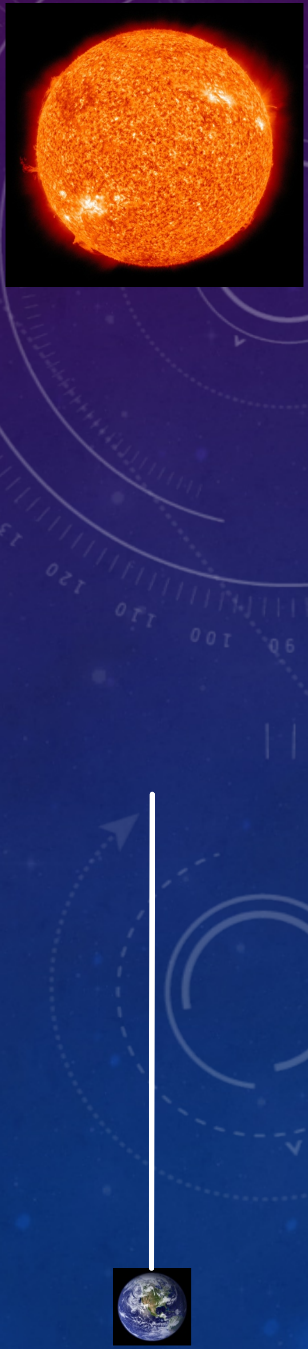
And solving for h gives us:

$h \approx 7.34 \times 10^{12}$ cm

SO WHAT DOES THAT MEAN?

- We would have to drop an H- ion from ~73 million km to yield a 750 KeV kinetic energy
- (assuming a constant value for g—not accurate, just a rough calculation)
- That's ~over 45 million miles
- Almost half the distance between Earth and the Sun!

SO WHAT DOES THAT MEAN?



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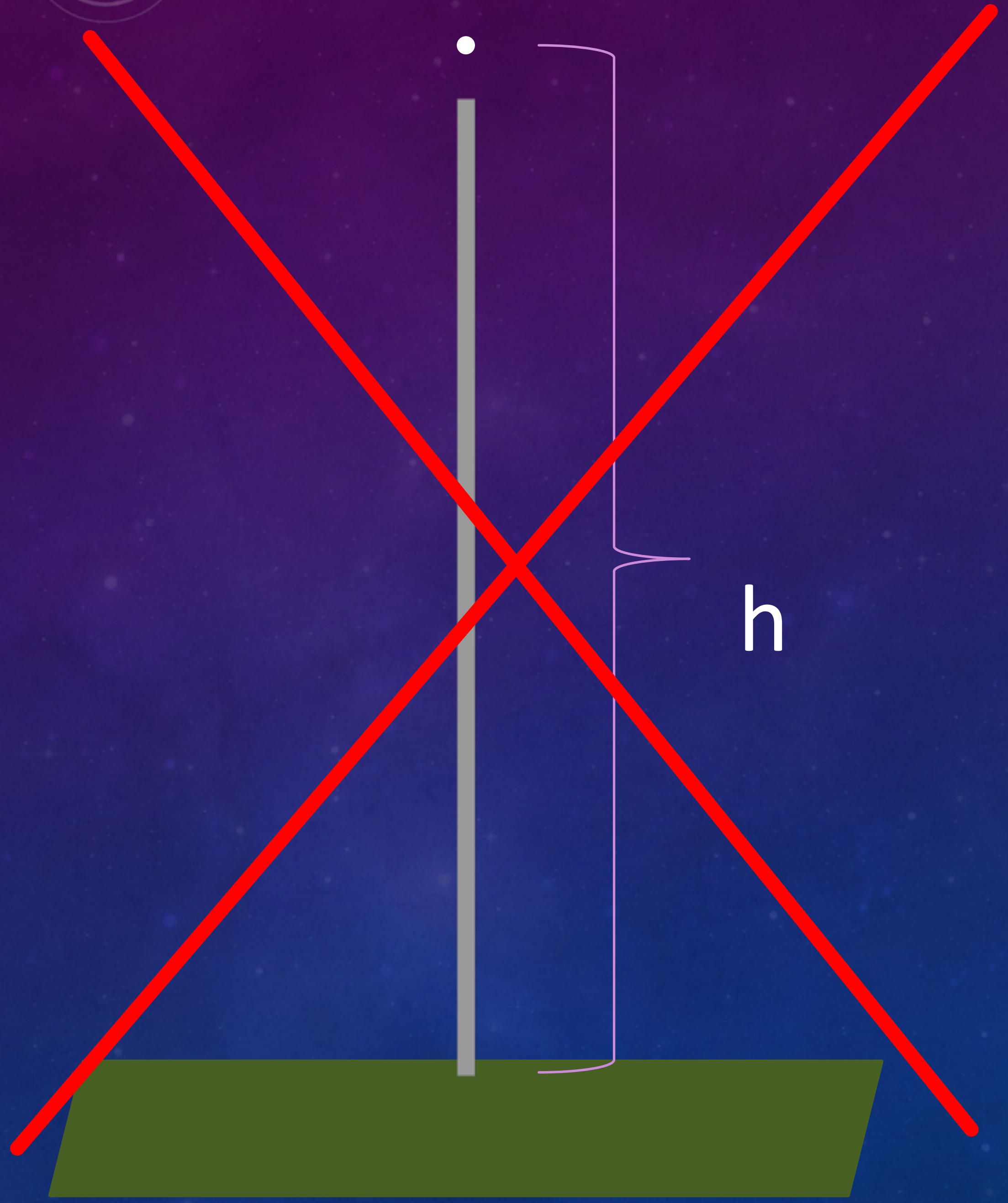
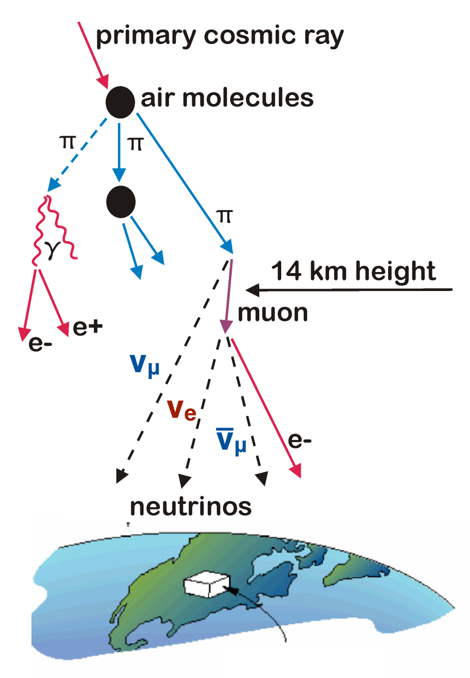
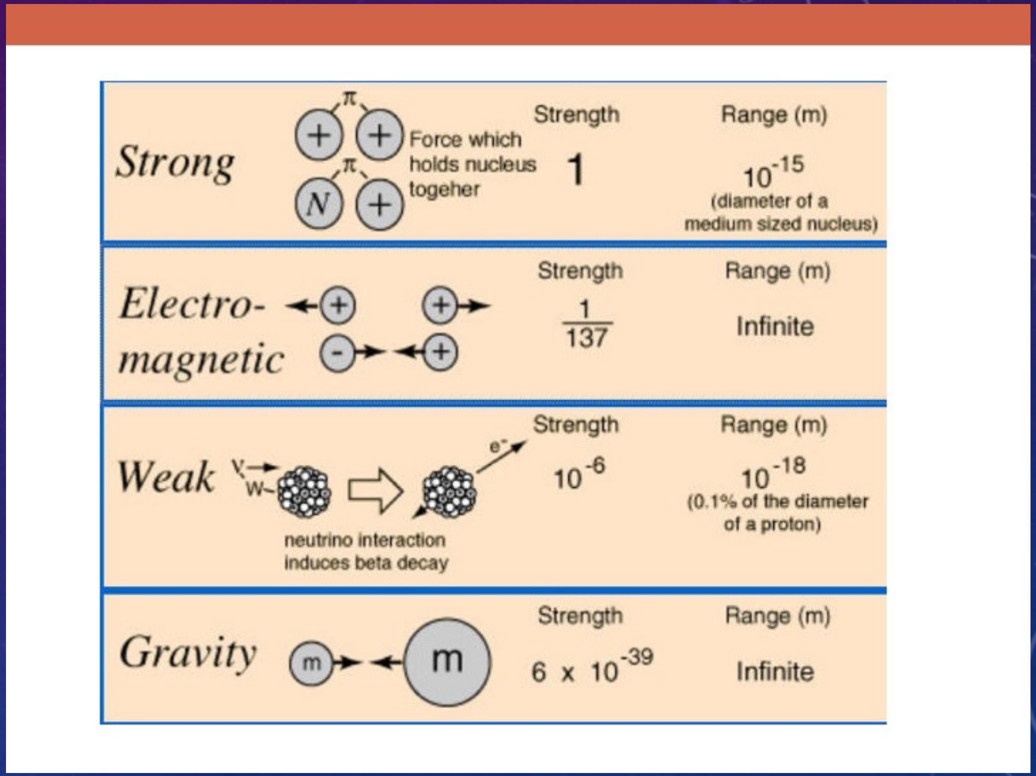

h

WE DO SCIENCE ON HUMAN SCALES

- A gravity accelerator would actually **work**, and very well, too
- Cosmic rays are particles entering the Earth’s atmosphere accelerated from outer space over huge distances by gravitational effects. We do actually do a LOT of physics using gravitationally accelerated particles.
- But for the kind of results we want to see, in the timescales and distances we want to see them, other methods are often more practical

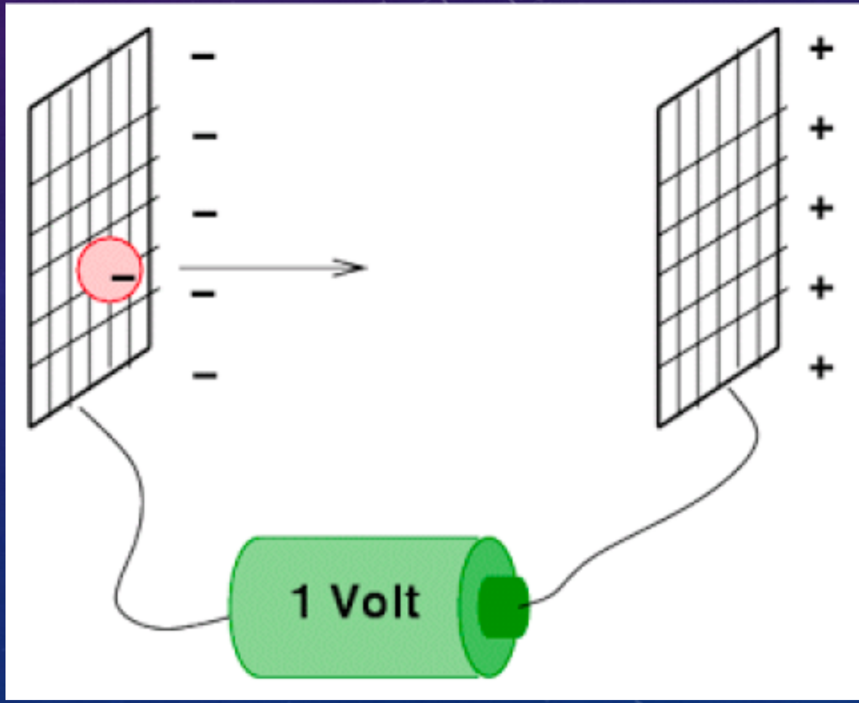


WHAT ABOUT THE ELECTROMAGNETIC FORCE?



EV

- eV = the amount of energy gained by accelerating one electron of charge over 1 Volt of electrical potential
- KeV (10^3), MeV (10^6), GeV (10^9), TeV (10^{12})
- Think of "electrical potential" like "gravitational potential"

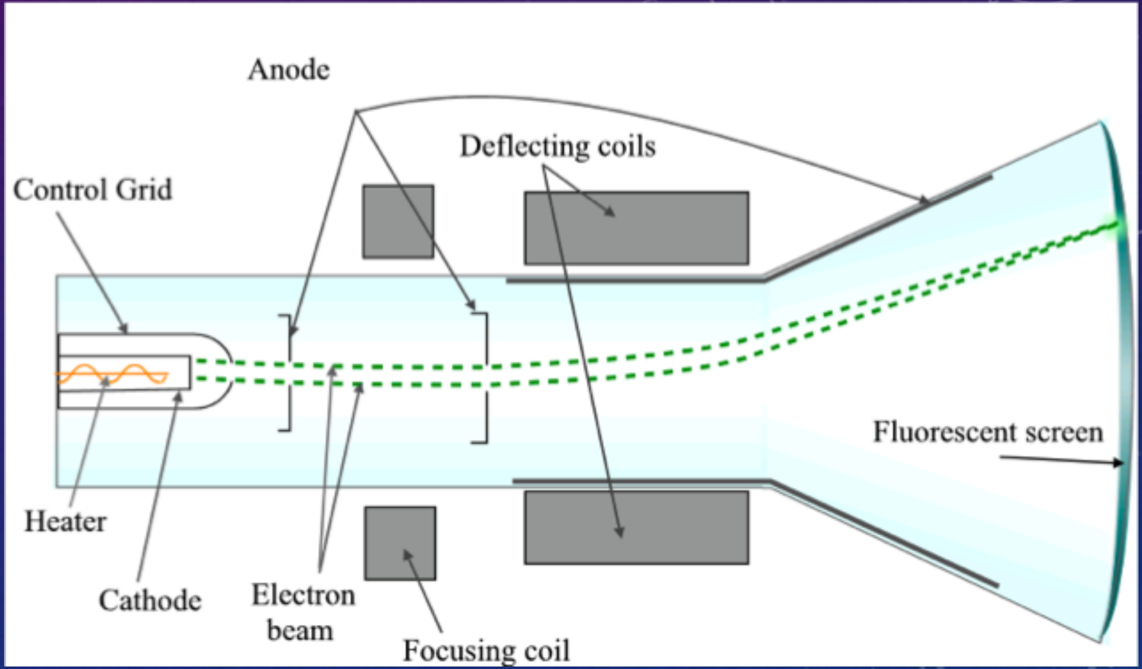


SO IF WE SET UP AN ELECTRICAL POTENTIAL…

- Would that accelerate a particle?
- Yes, and some “Electrostatic” accelerators work just like that.
- Examples: Crooke’s tube, Van de Graaf generator, Cockcroft-Walton

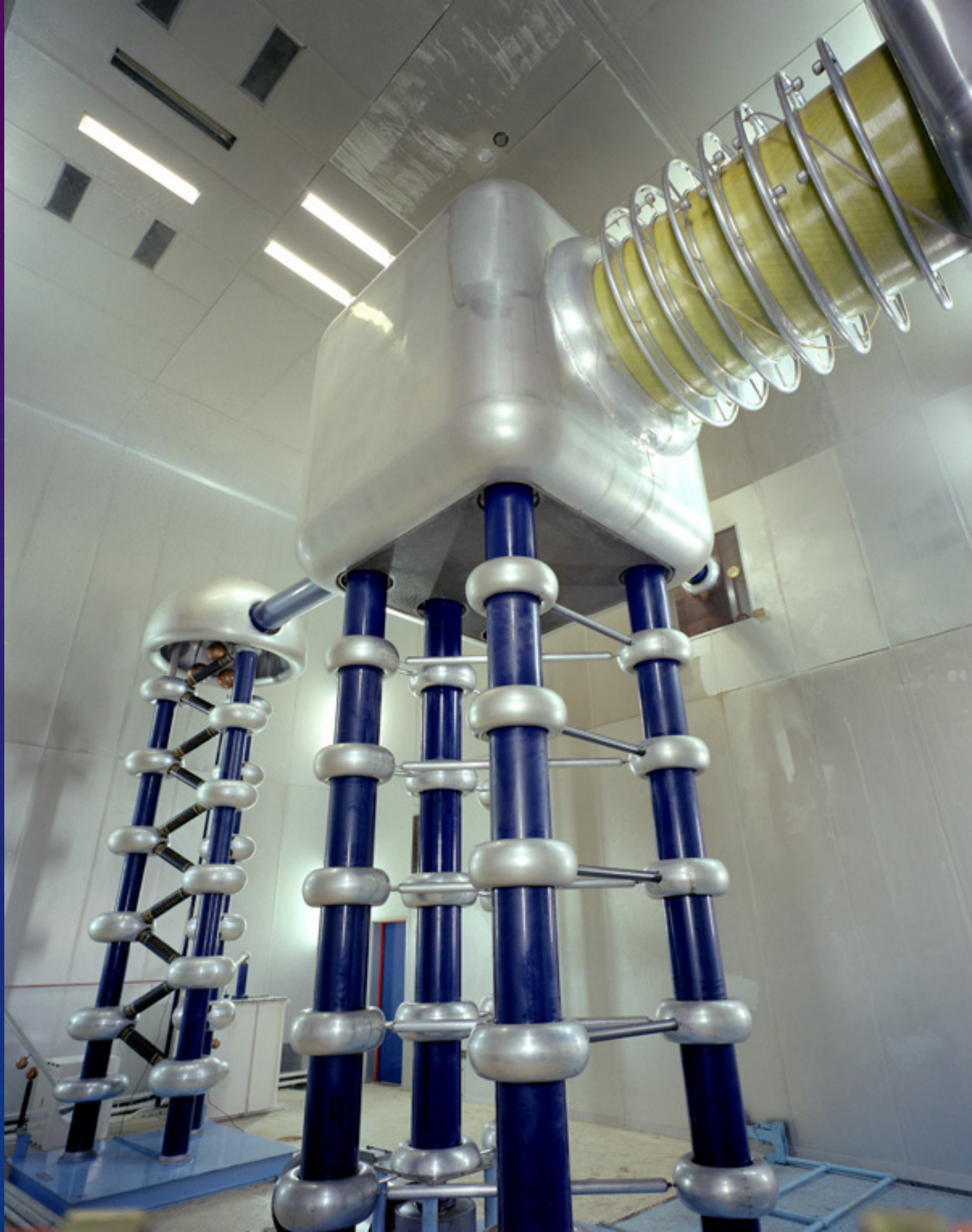
CROOKE'S TUBE (CATHODE RAY TUBE): 1870

- Voltage differential created across a cathode-anode pair
- Negatively charged electrons are attracted to the anode, strike screen and glow
- Charged plates used for control
- This technology is used in CRT screens



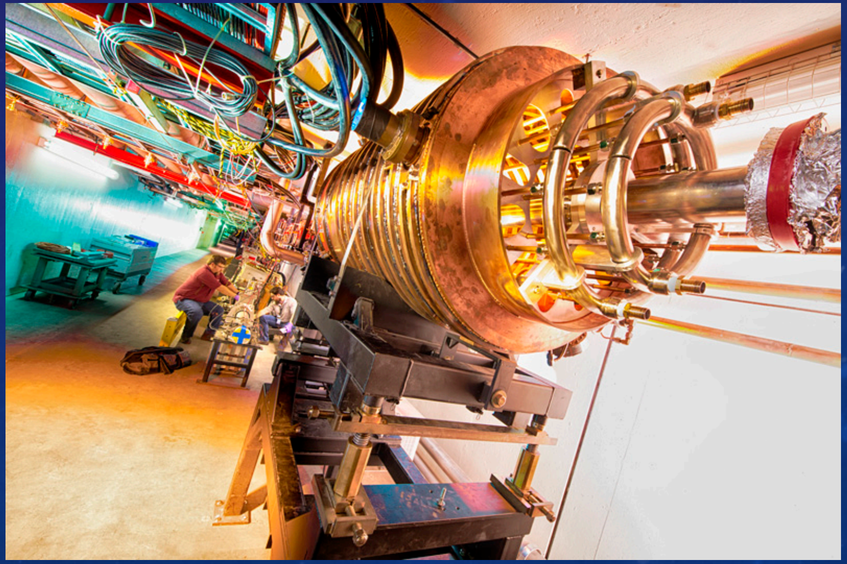
COCKCROFT-WALTON: 1928-1930

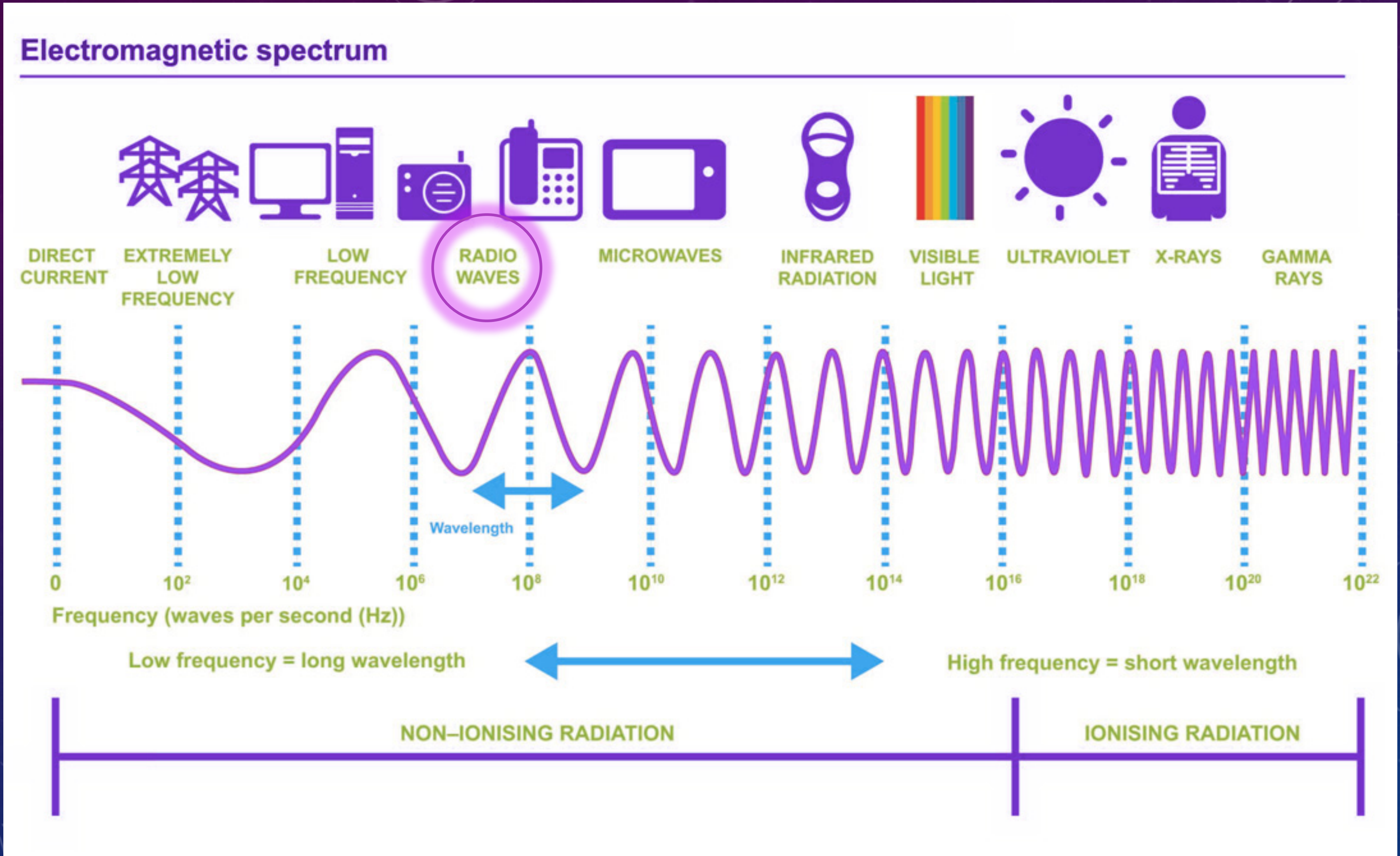
- Clever design, very high voltages possible
- Limitations—breakdown voltage, sparking
- First accelerating structure in Fermilab's accelerator chain from 1968 to 2012: accelerated hydrogen ions(H-) to 750 KeV



ELECTROSTATIC → ELECTRODYNAMIC

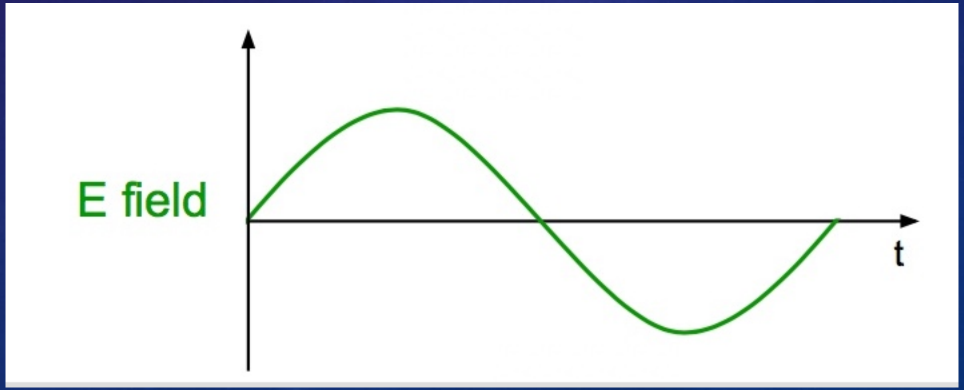
- Limit to what is achievable; eventual voltage breakdown. To reach higher energies, we need to come up with another way.
- What about lots of small, lower-voltage pushes instead of one mighty super-high-voltage push?
- **RF cavities are how we accelerate and manipulate particles.**
    - RF = radio frequency, the band of the energy used.




Electromagnetic spectrum
DIRECT CURRENT
EXTREMELY LOW FREQUENCY
LOW FREQUENCY
RADIO WAVES
MICROWAVES
INFRARED RADIATION
VISIBLE LIGHT
ULTRAVIOLET
X-RAYS
GAMMA RAYS
Wavelength
0
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}
10^{22}
Frequency (waves per second (Hz))
Low frequency = long wavelength
High frequency = short wavelength
NON–IONISING RADIATION
IONISING RADIATION

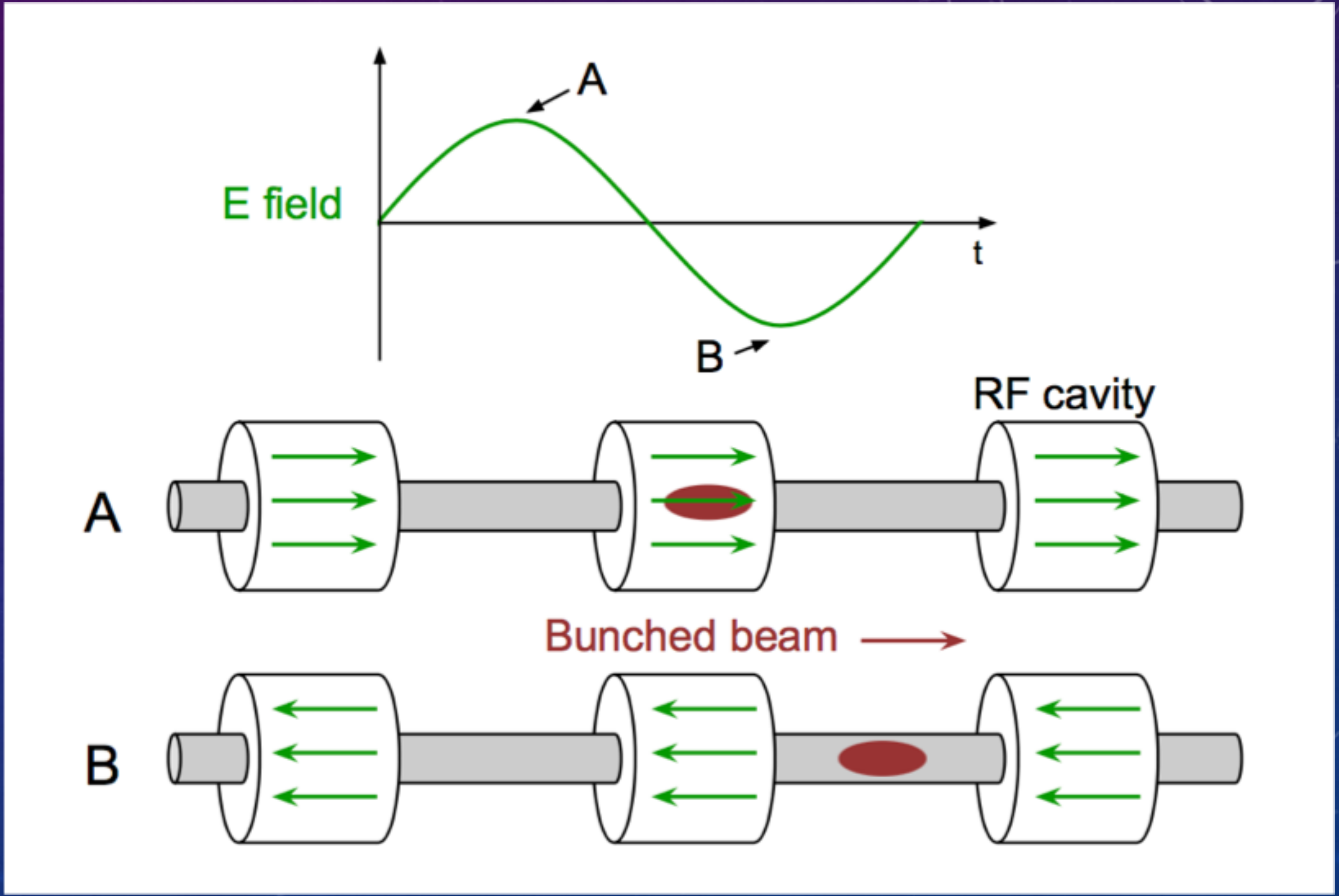
DRIFT TUBE LINAC (ALVAREZ LINAC)

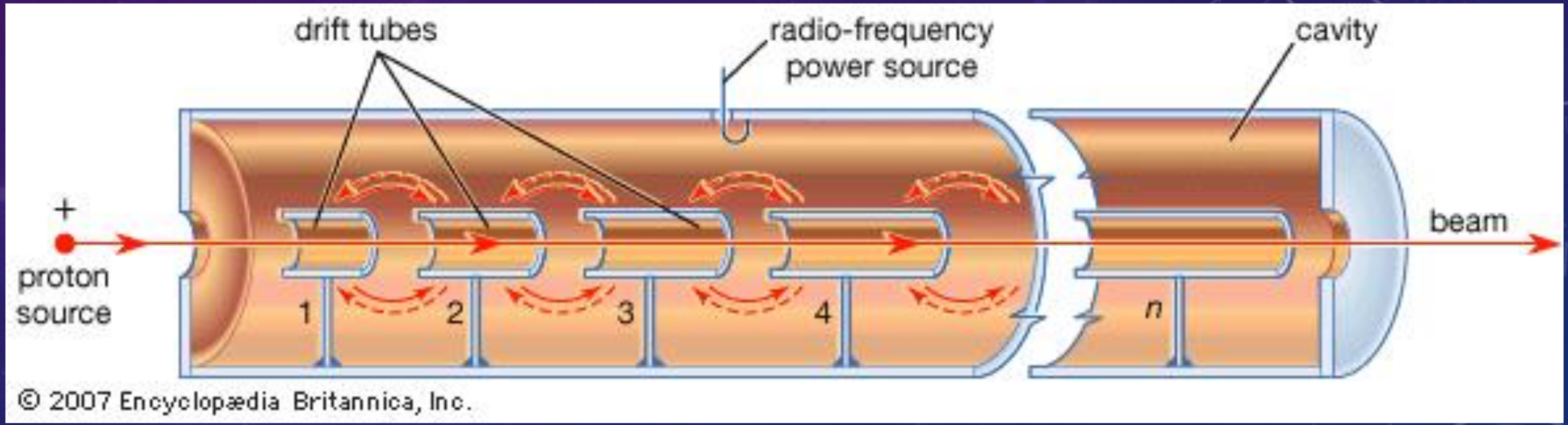
- Metallic structure in which oscillating electric fields are produced and controlled
- When a charged particle encounters an electric field, it experiences a force (a “push”)
- This push makes it gain a bit of energy and accelerates it
- But field is oscillating. What about the part that points in the ”wrong” direction?



DRIFT TUBE LINAC (ALVAREZ LINAC)

- But field is oscillating. What about the part that points in the ”wrong” direction?
- Drift tubes block out field; sequence of accelerating gaps and drift tubes are designed so particles only encounter the fields we want at the times we want
- As the particles travel faster and faster, they cover more distance in the same amount of time
- Drift tubes get longer and longer




drift tubes
radio-frequency power source
cavity
+
proton source
1
2
3
4
n
beam
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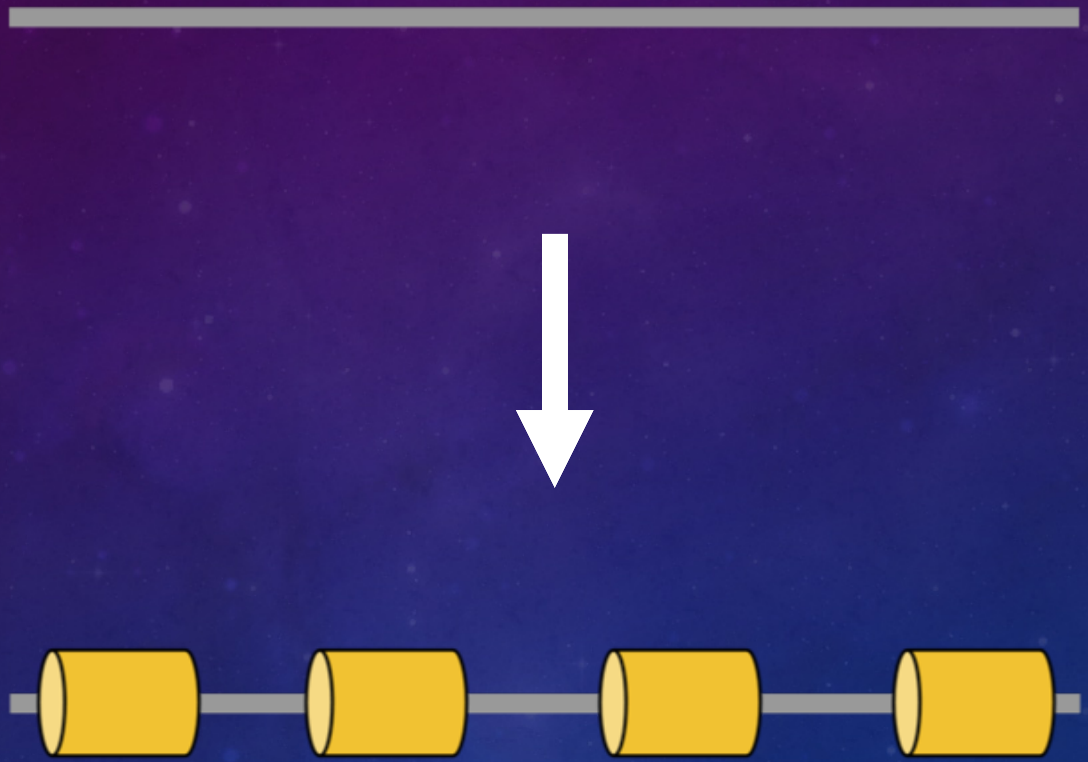

WE HAVE AN ACCELERATOR!

- Now we’re in business. Nobel Prize, here we come!

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- What if we want to hit very high energies?

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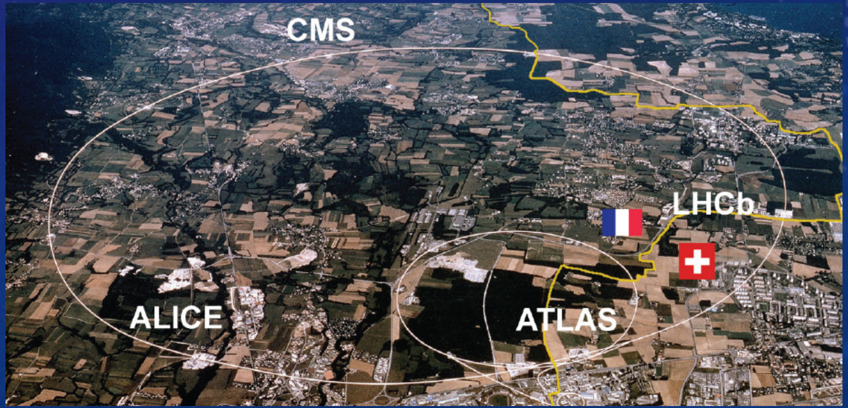
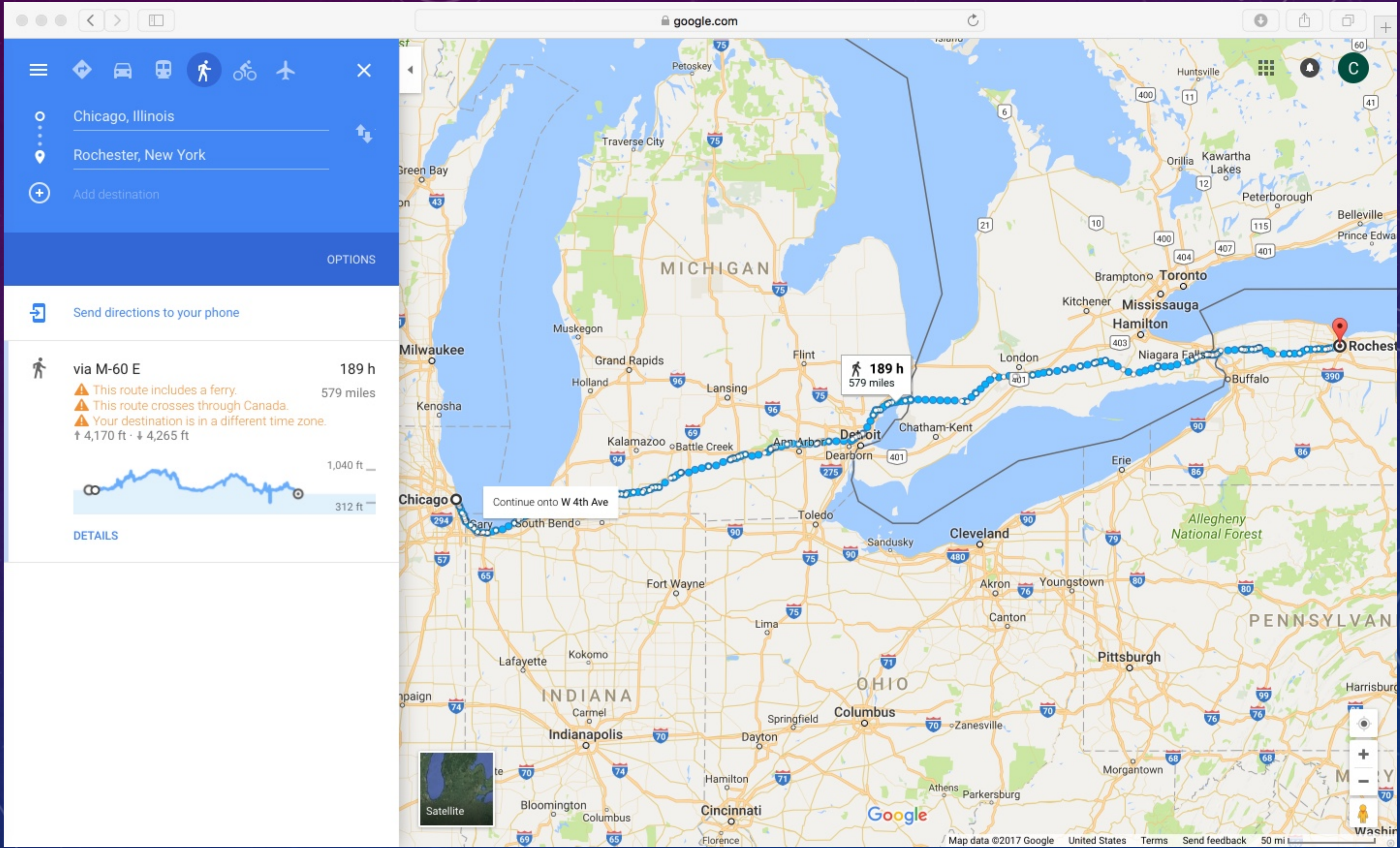
- Stanford Linear Accelerator (SLAC)’s linac accelerated electrons up to 50 GeV in 2.0 miles—longest built

WE HAVE AN ACCELERATOR!

- Now we're in business. Nobel Prize, here we come!
- What if we want to hit very high energies?
- Stanford Linear Accelerator (SLAC)'s linac accelerated electrons up to 50 GeV in 2.0 miles—longest built
- LHC energy gets up to 13 TeV, which (if same energy in equivalent linac) comes out to 260 SLACs or 520 miles

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Chicago, Illinois
Rochester, New York
Add destination
OPTIONS
Send directions to your phone
via M-60 E
189 h
579 miles
This route includes a ferry.
This route crosses through Canada.
Your destination is in a different time zone.
4,170 ft · 4,265 ft
1,040 ft
312 ft
DETAILS
189 h
579 miles
Continue onto W 4th Ave
MICHIGAN
INDIANA
OHIO
PENNSYLVANIA
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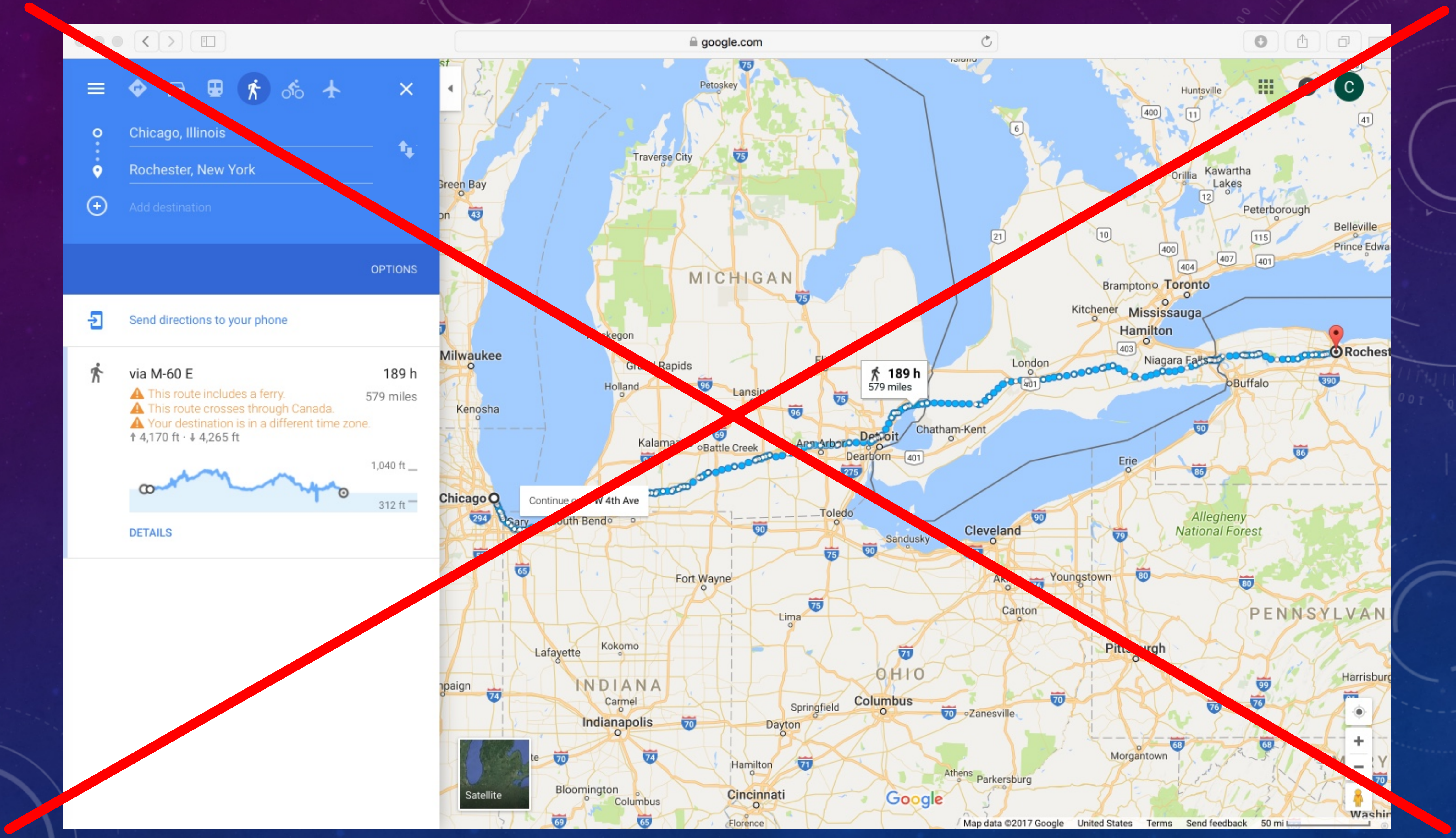
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MICHIGAN
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Map data ©2017 Google
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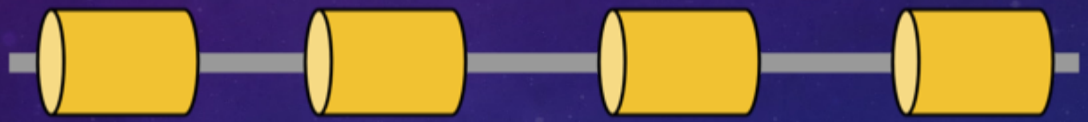
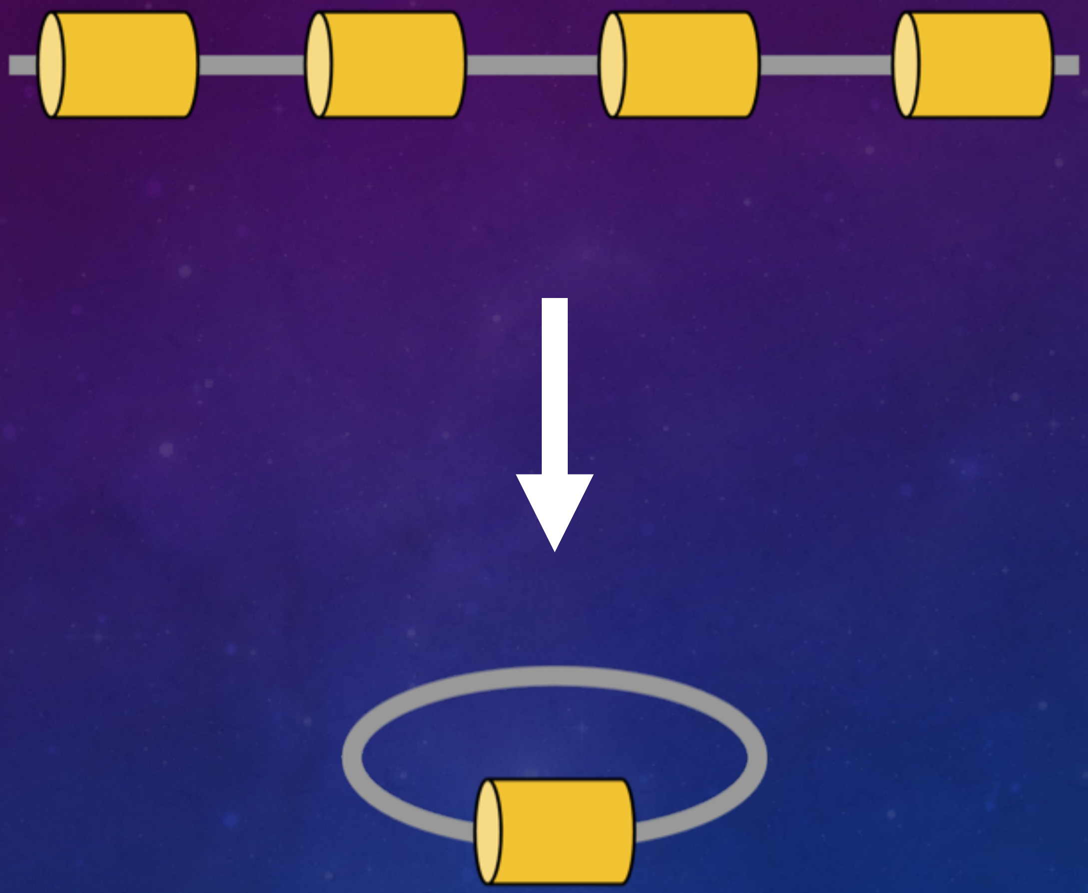




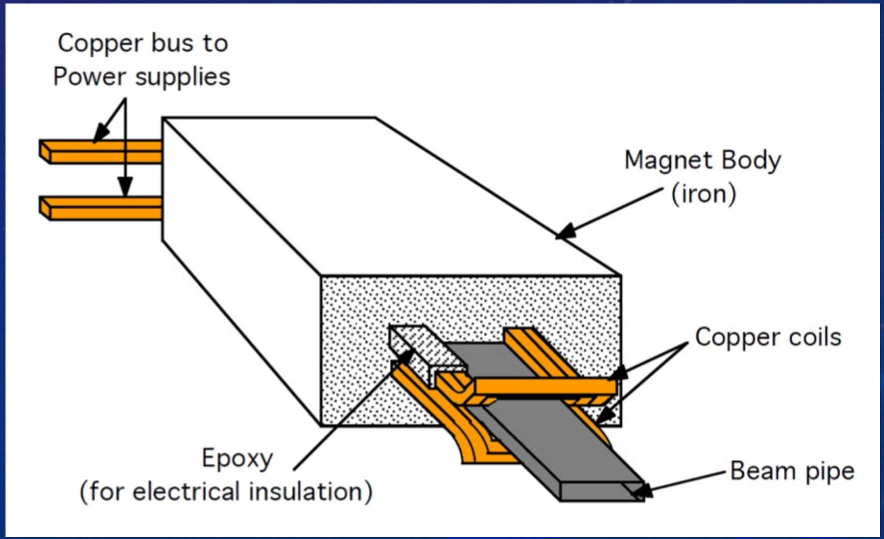
SO HOW DO YOU BEND A CHARGED PARTICLE?

SO HOW DO YOU BEND A CHARGED PARTICLE?

- A charged particle bends in a magnetic field.

MAGNETIC FIELDS AND FORCES

- Moving charged particles (a.k.a. electric currents) produce magnetic fields
  - Electromagnets!
- Those fields interact with other moving charged particles and exert forces on them
- **Magnets are how we bend and focus beams of particles.**
- $\vec{F} = q\,\vec{v} \times \vec{B}$: the Lorentz Force

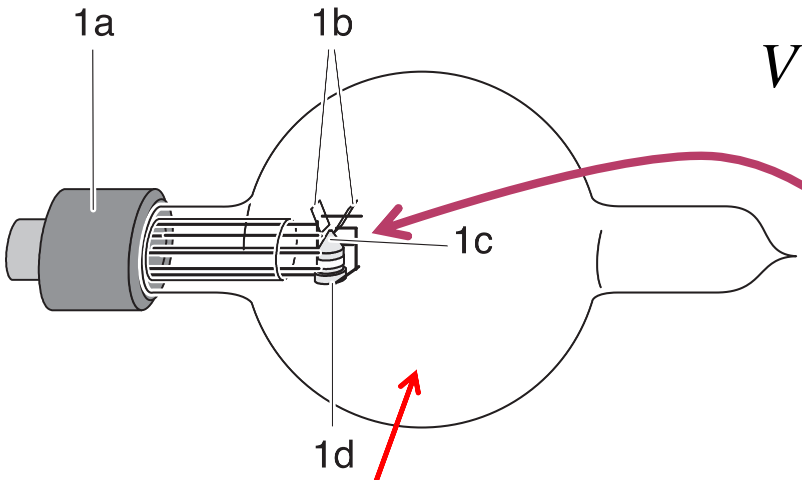


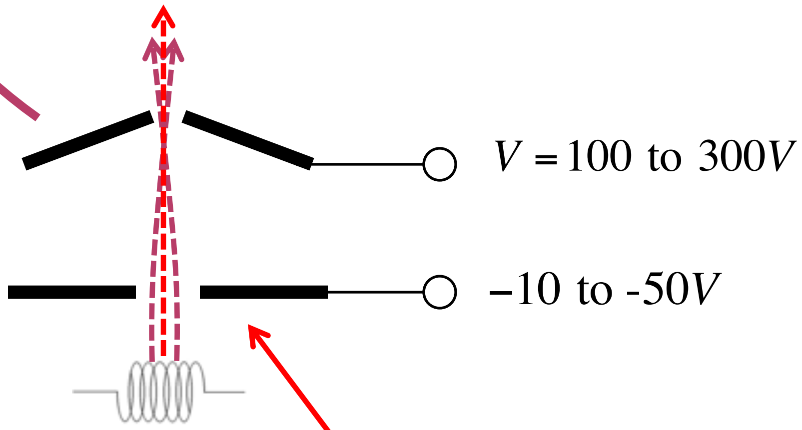
Fine beam tube/Helmholtz coil demonstration

- The tube generates an electron beam using a hot filament/cathode, “Wehnelt Cylinder”, and accelerating anode.

$$eV = \frac{1}{2}mv^2 \rightarrow v = \sqrt{\frac{2eV}{m}} \propto \sqrt{V}$$

$$V = 150\text{V} \rightarrow v = 7.3\times 10^6\,\text{m/s} = .024c$$





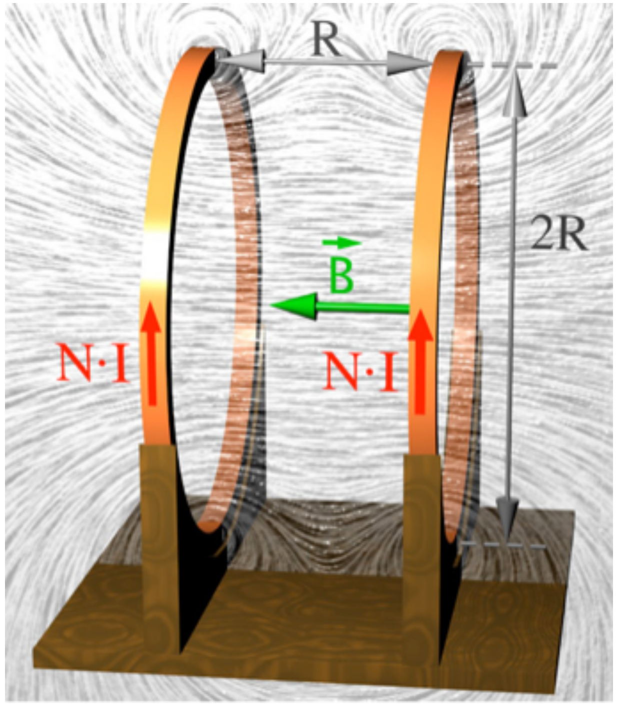
Filled with low pressure Hydrogen, which fluoresces when electrons pass through

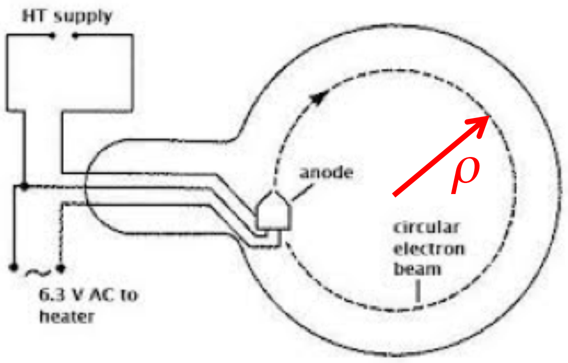
Heated filament (electron source)

Wehnelt Cylinder focuses electrons

Demo (cont'd)

- The Helmholtz Coils produce a ~uniform magnetic field



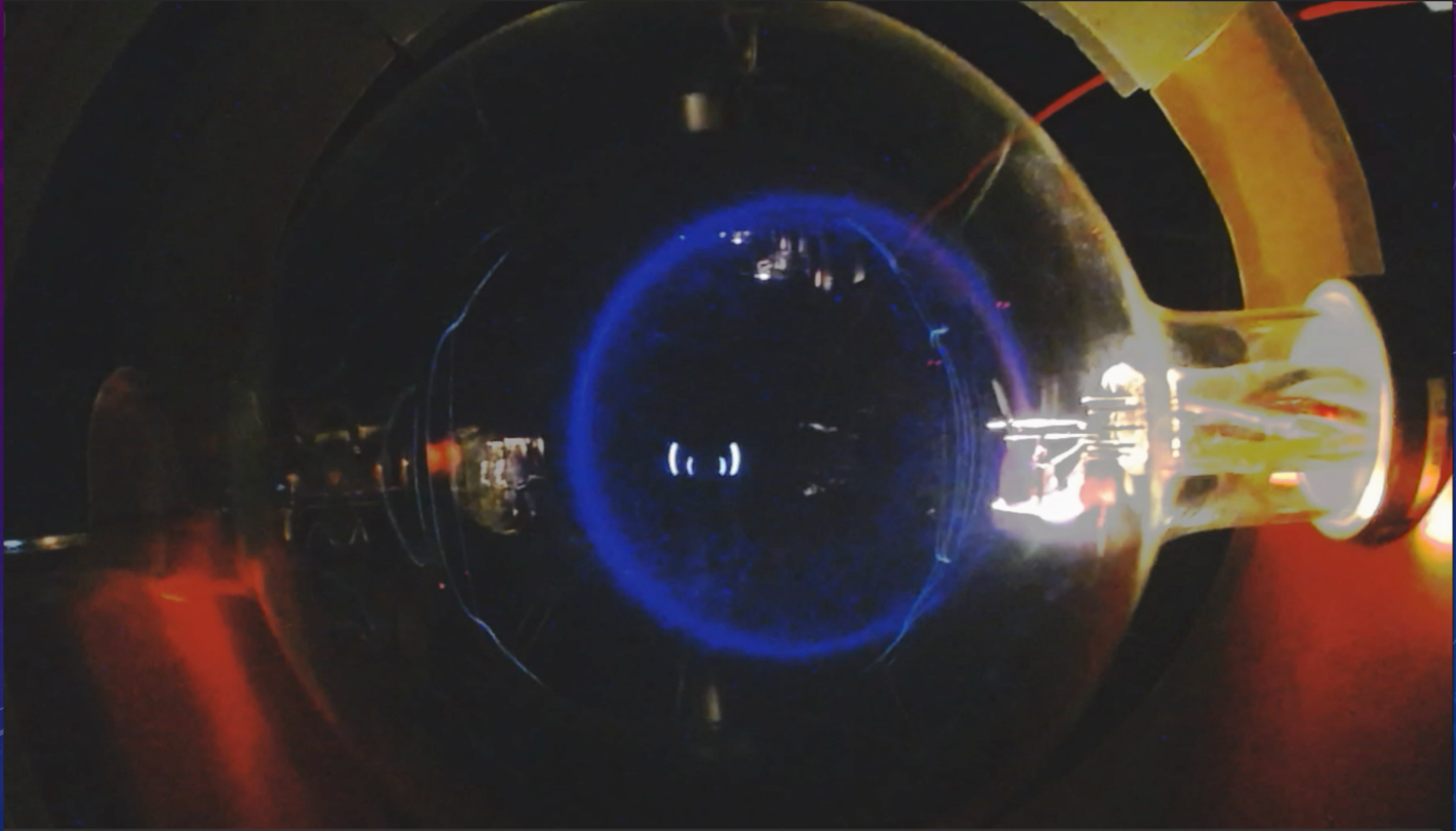


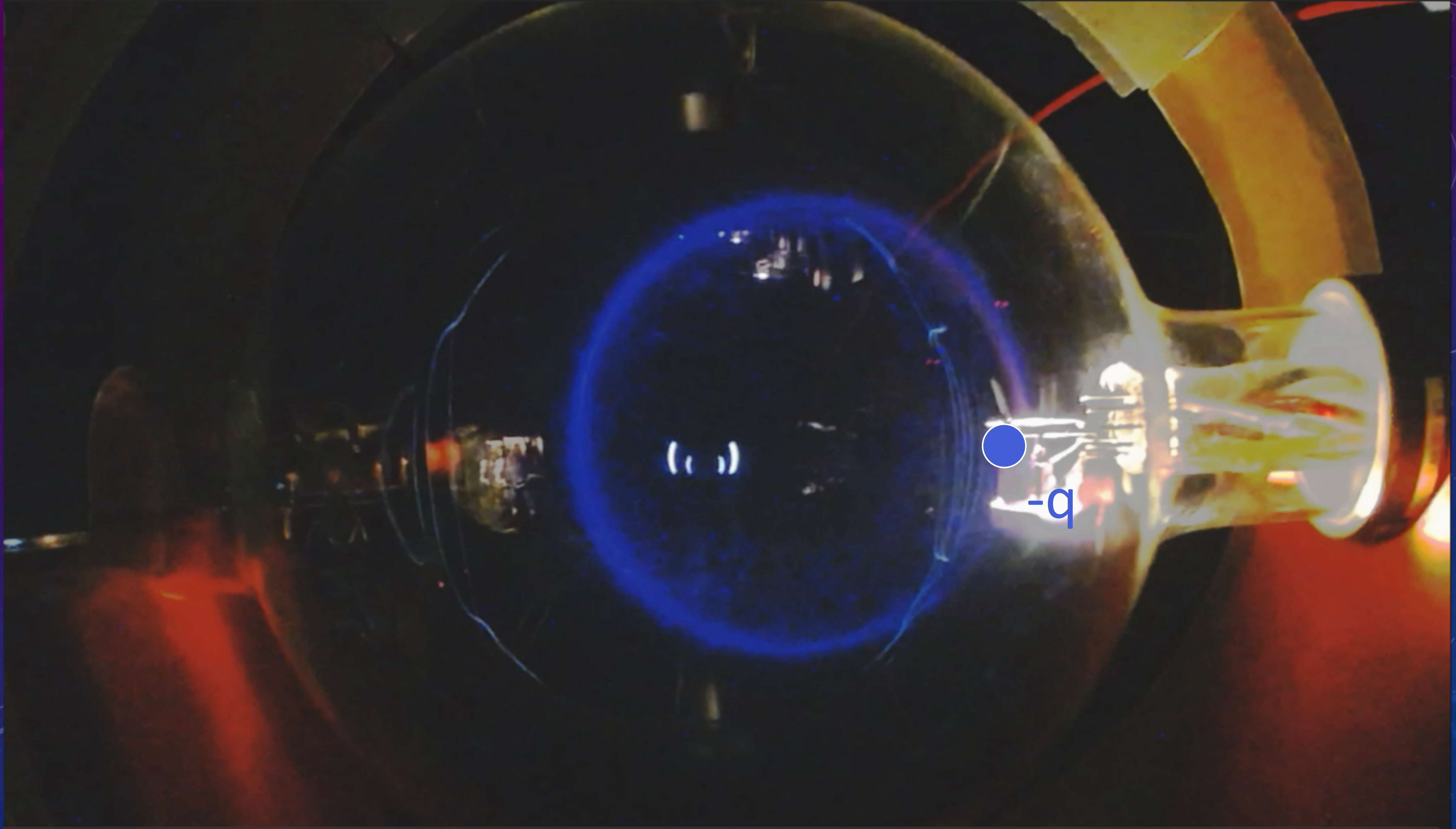
$$B=\left(\frac{4}{5}\right)^{\frac{3}{2}}\frac{\mu_0 NI}{R}\propto I$$

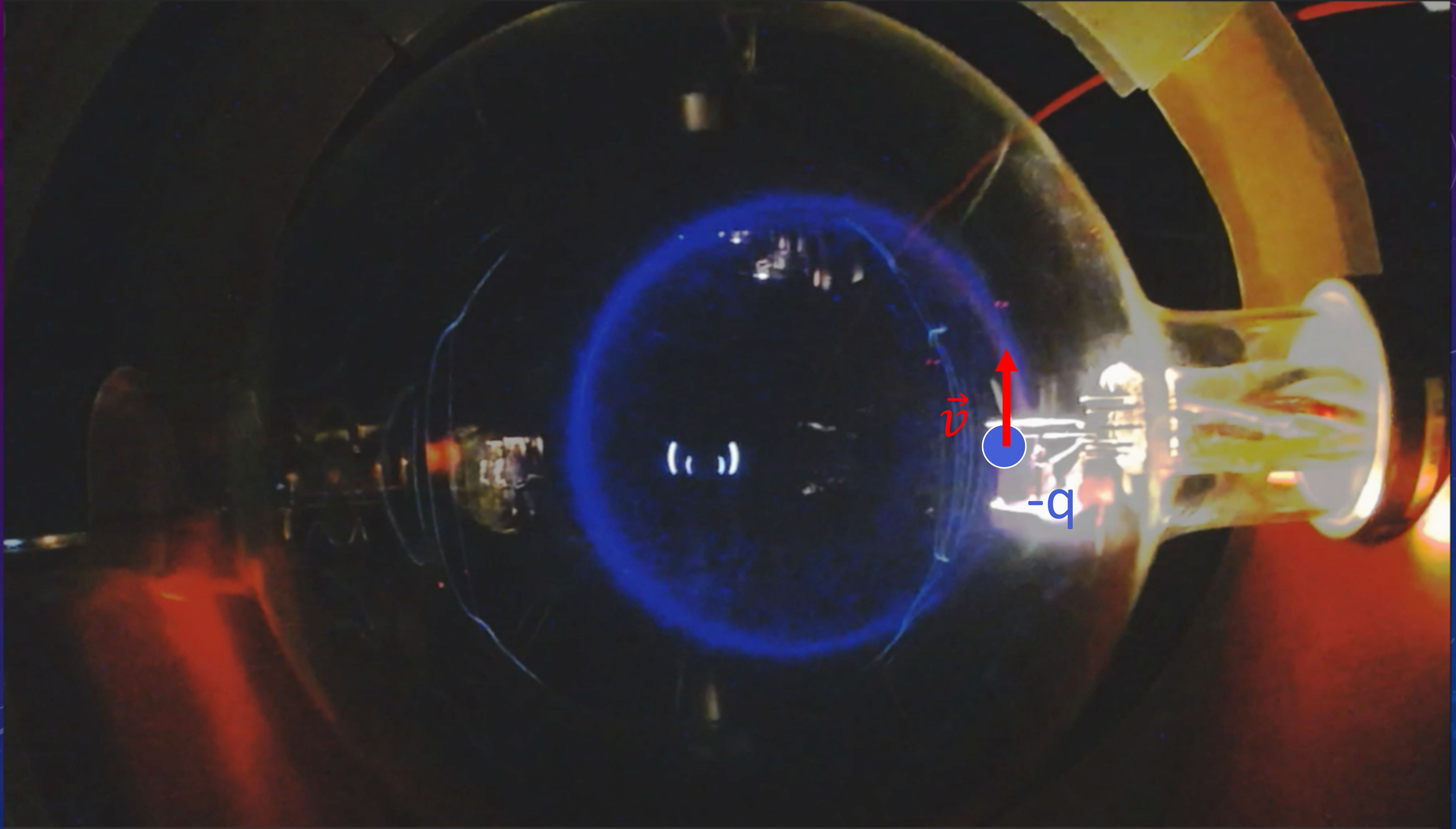
$$\rho=\frac{mv}{eB}$$

$$\propto\frac{v}{B}$$

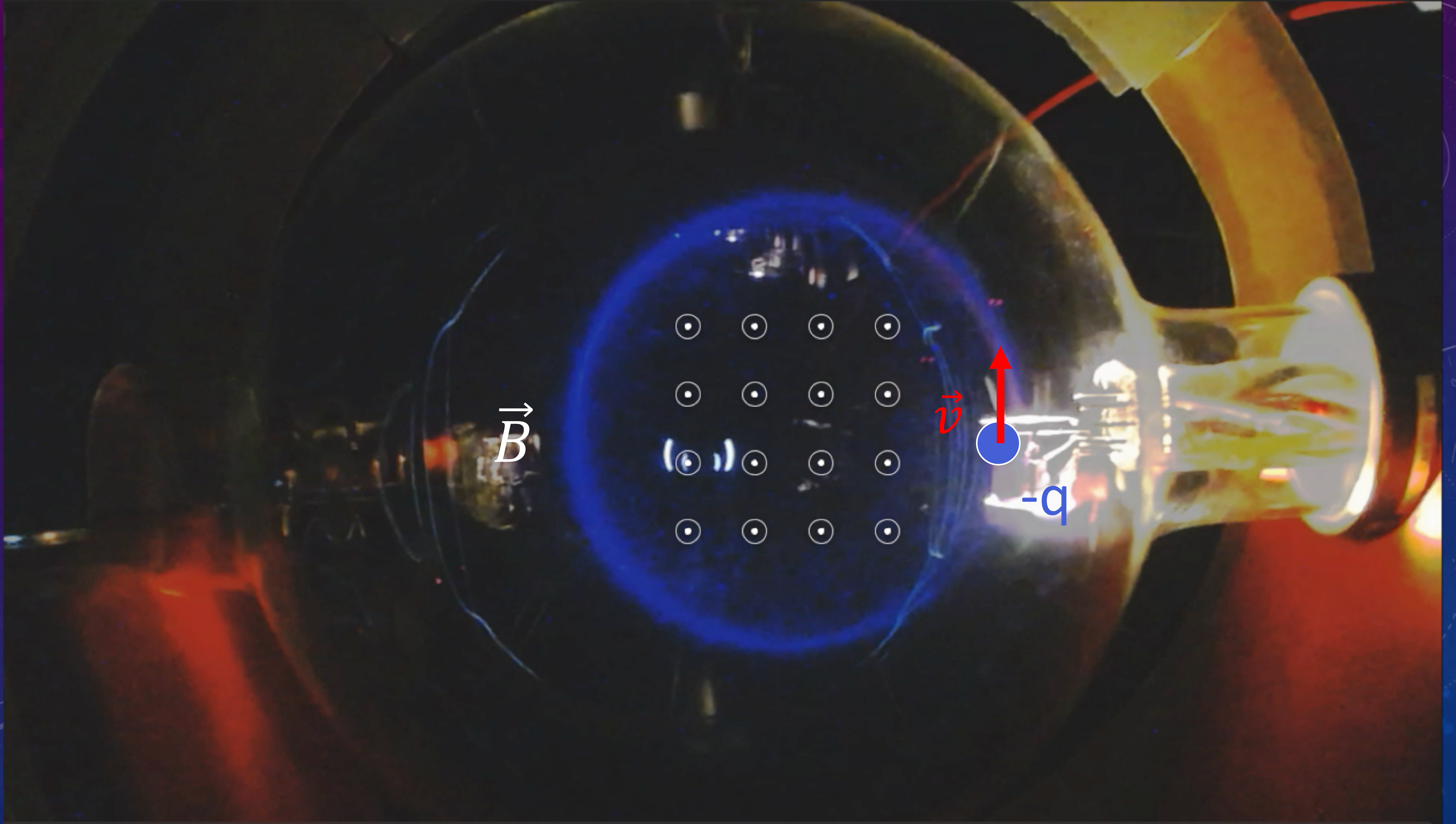
$$\propto\frac{\sqrt{V}}{I}$$




-q

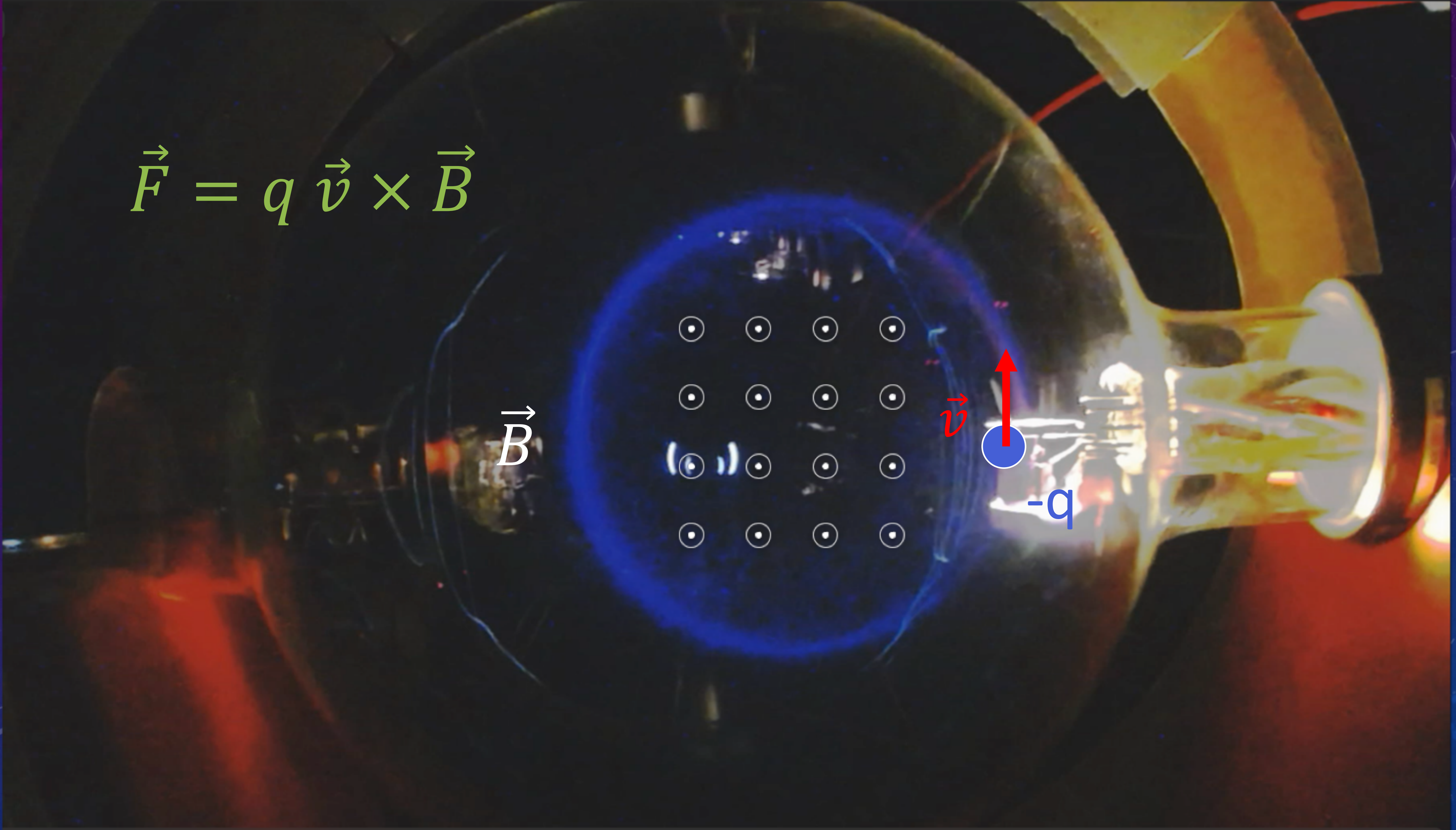


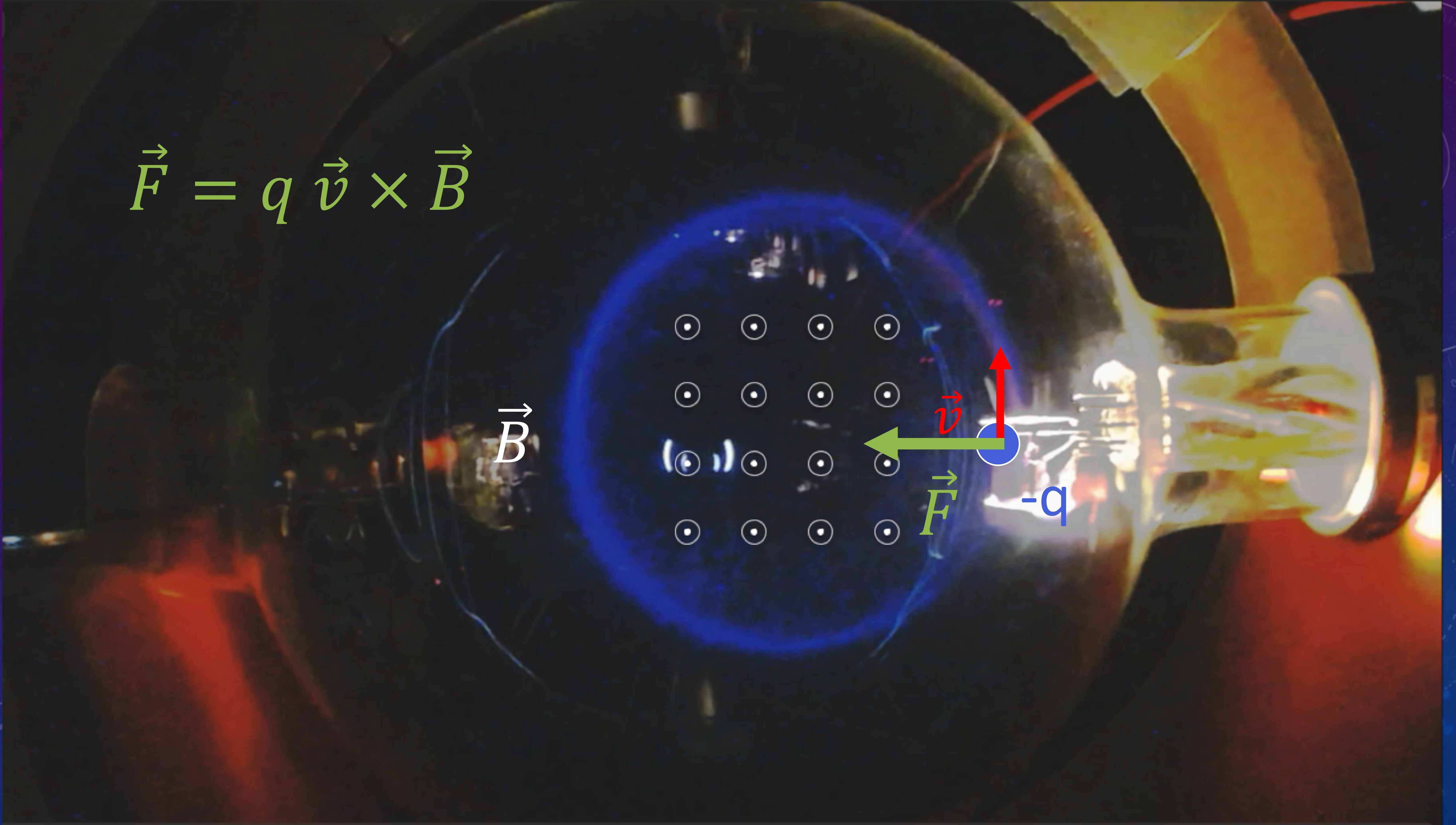
$\vec{v}$
-q



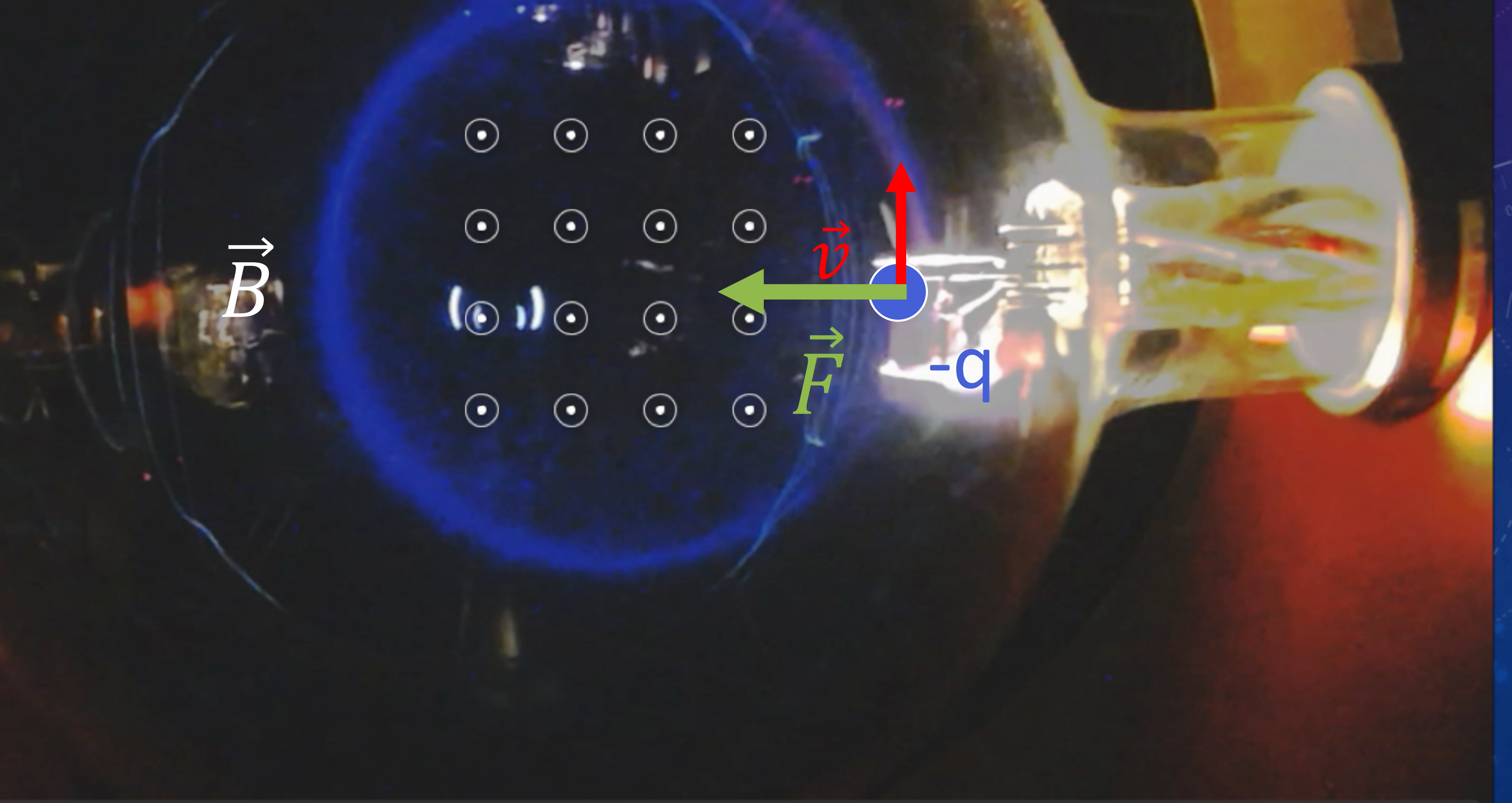
$\vec{B}$
$\vec{v}$
-q

$$\vec{F} = q\,\vec{v} \times \vec{B}$$

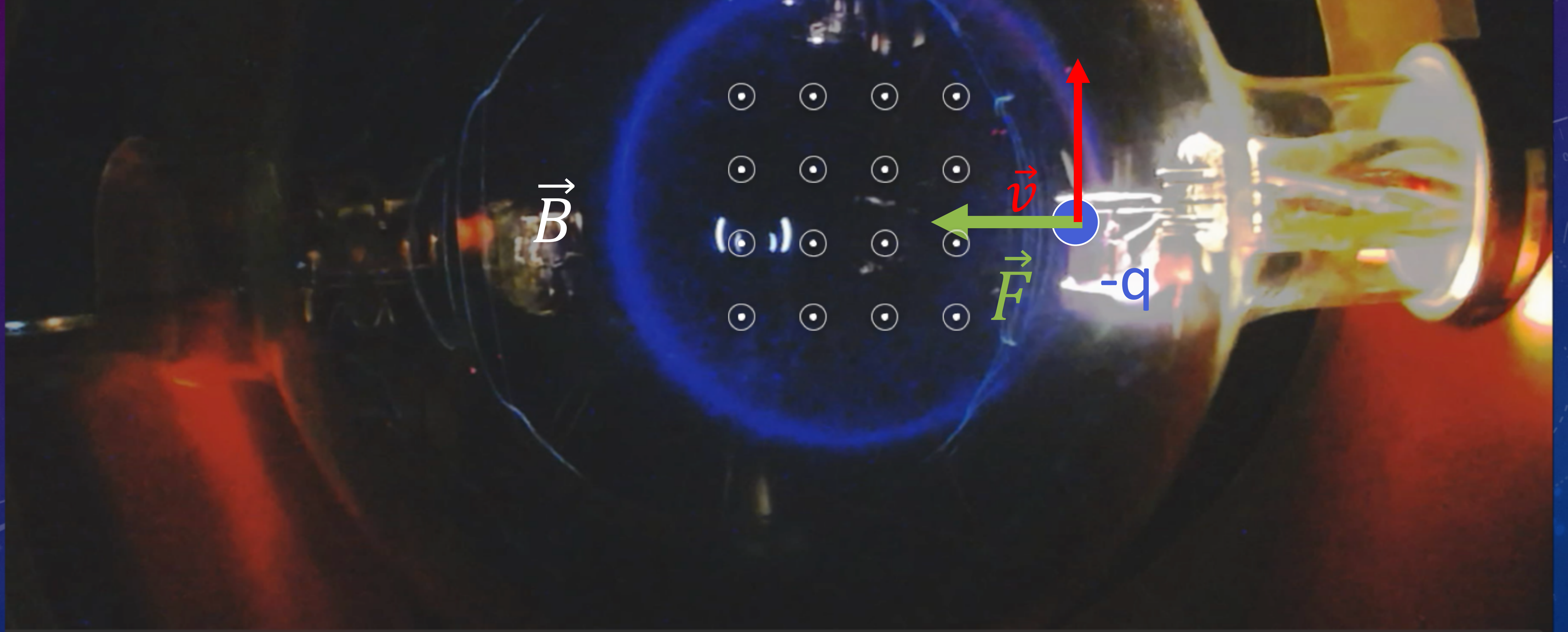



$\vec{F} = q\,\vec{v} \times \vec{B}$
$\vec{B}$
$\vec{v}$
$\vec{F}$
-q

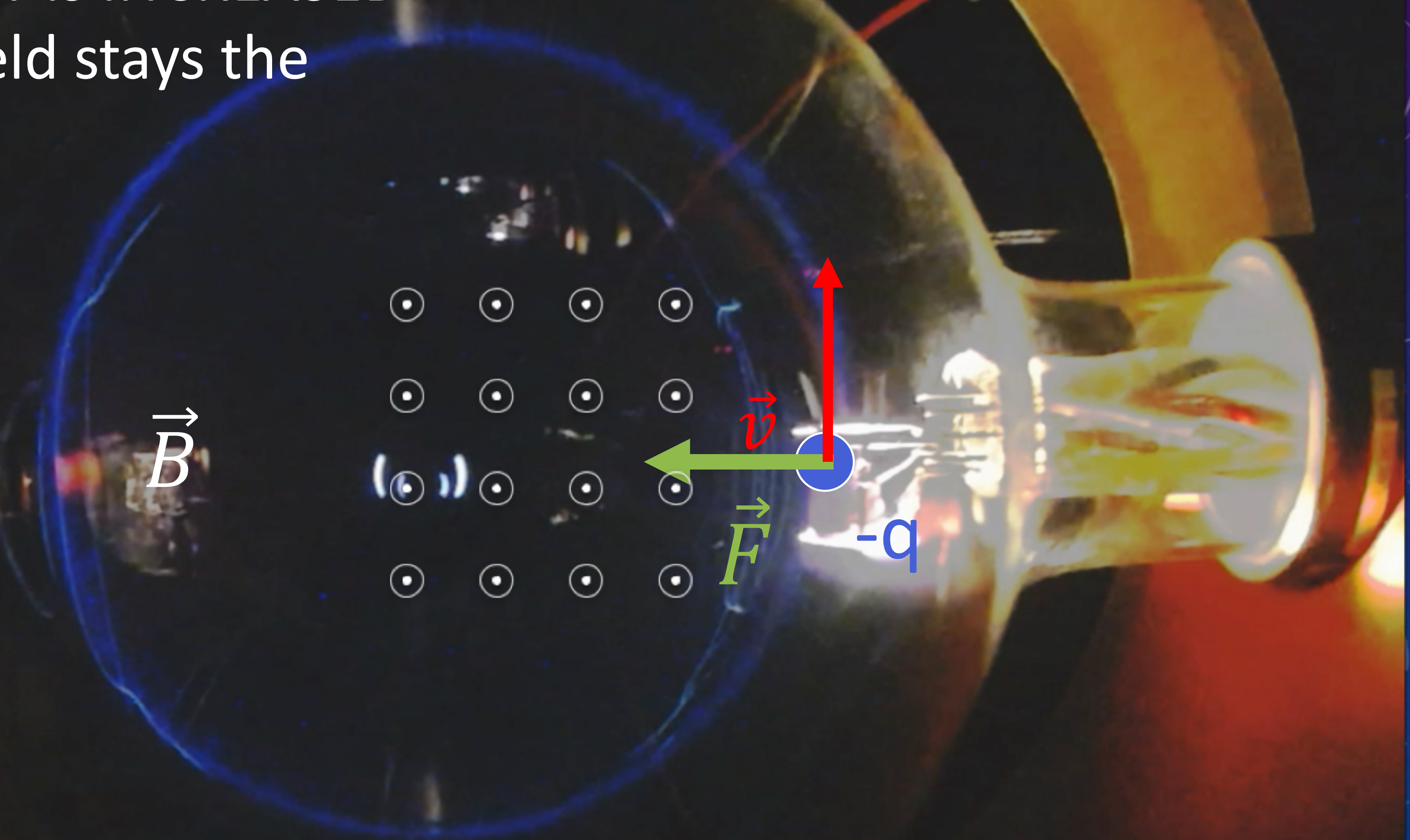
What if VELOCITY is INCREASED and magnetic field stays the same?



What if VELOCITY is INCREASED and magnetic field stays the same?

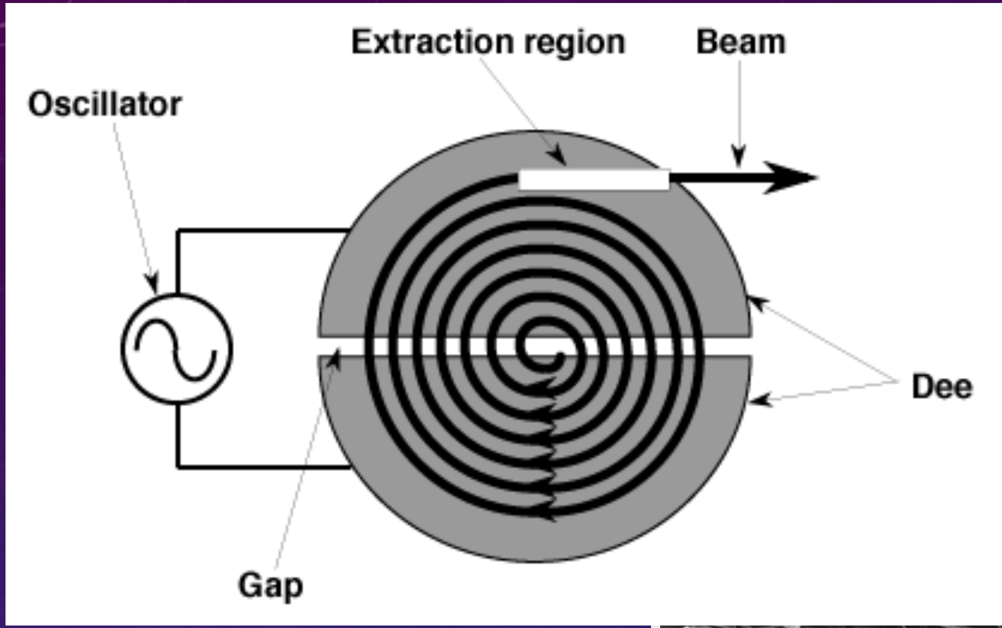


What if VELOCITY is INCREASED and magnetic field stays the same?

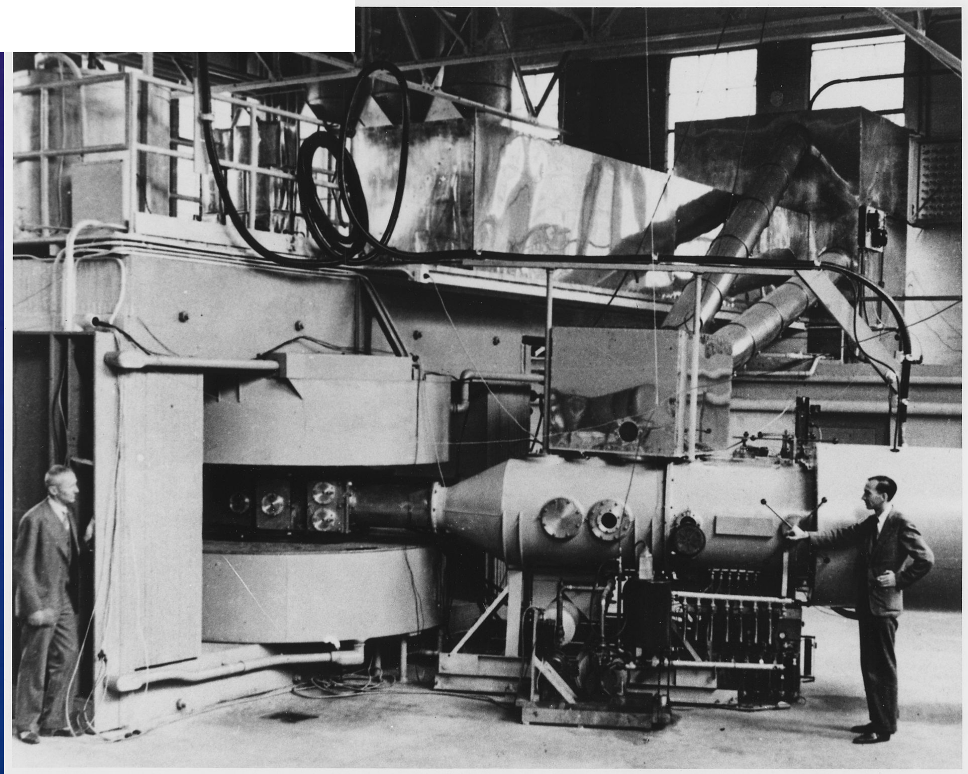


Radius of circle gets larger

CYCLOTRON

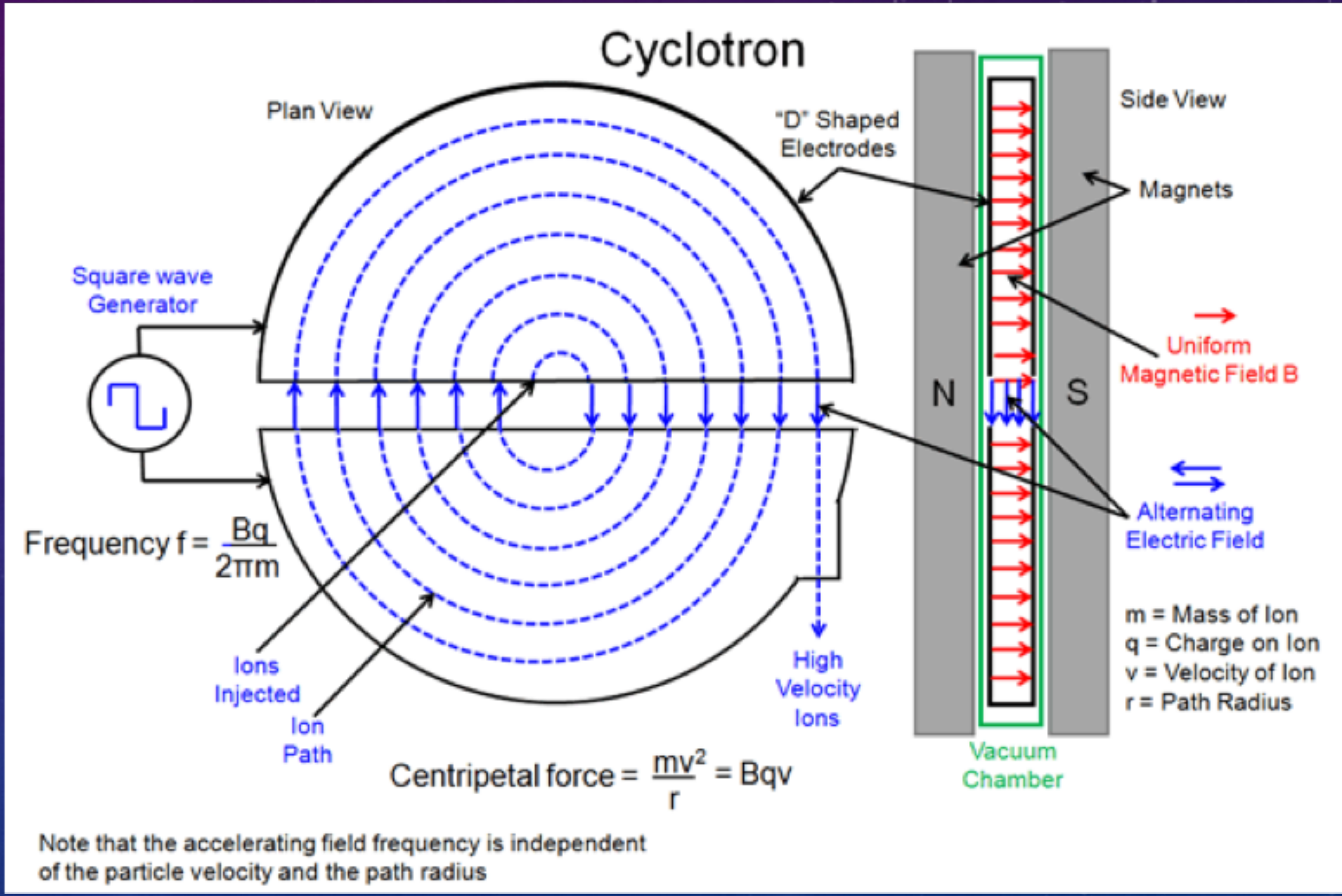


- The cyclotron uses:
  - A split RF cavity (Dees)
  - A large split magnet to produce a uniform magnetic field

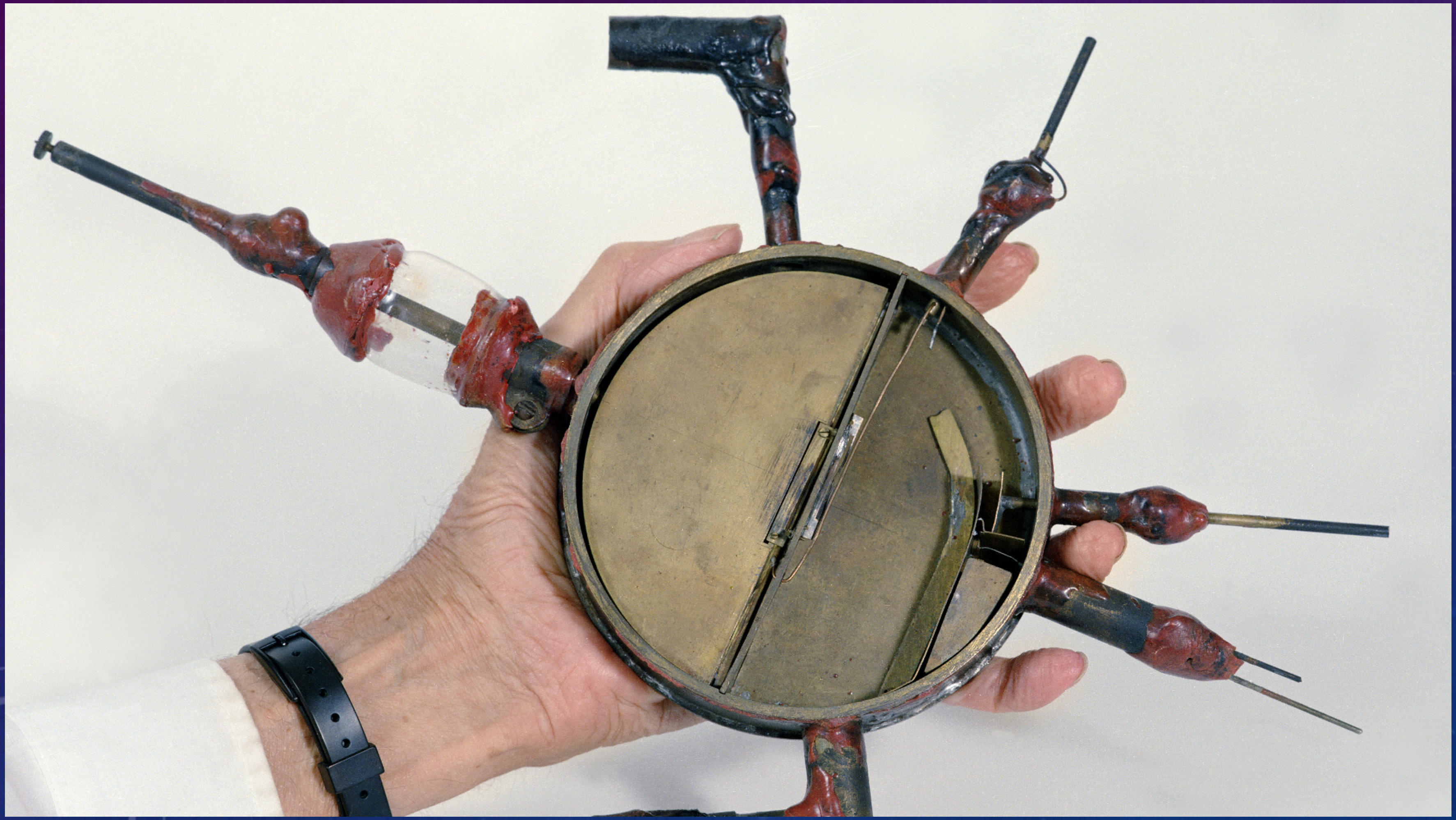


CYCLOTRON

- It's a bit like a drift tube linac, but stretched out and curled around
- Characteristic spiral pattern as particle accelerates and radius of curvature gets larger
- Often used today for medical purposes: proton therapy, production of medical isotopes. Compact, cost-effective, reliable.



E. O. LAWRENCE’S CYCLOTRON



1939

103

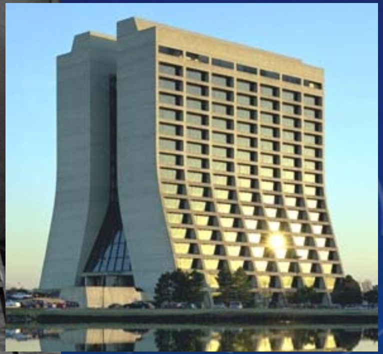
Lr

LAWRENCIUM

1961

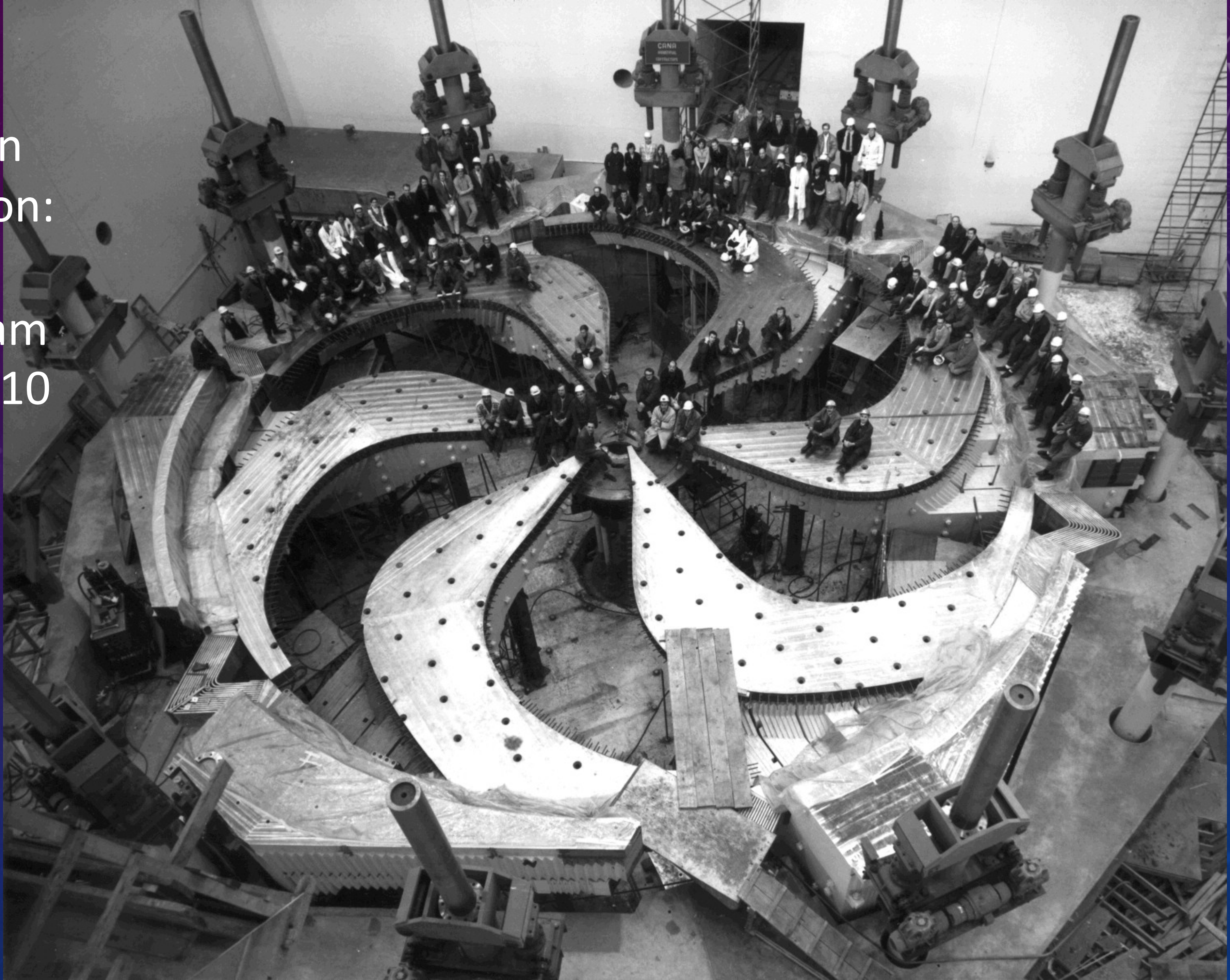
Lawrence Berkeley Lab 60 inch (diameter) cyclotron magnet

Robert Rathbun Wilson, founding director of Fermilab



Fermilab's iconic Wilson Hall is named after him

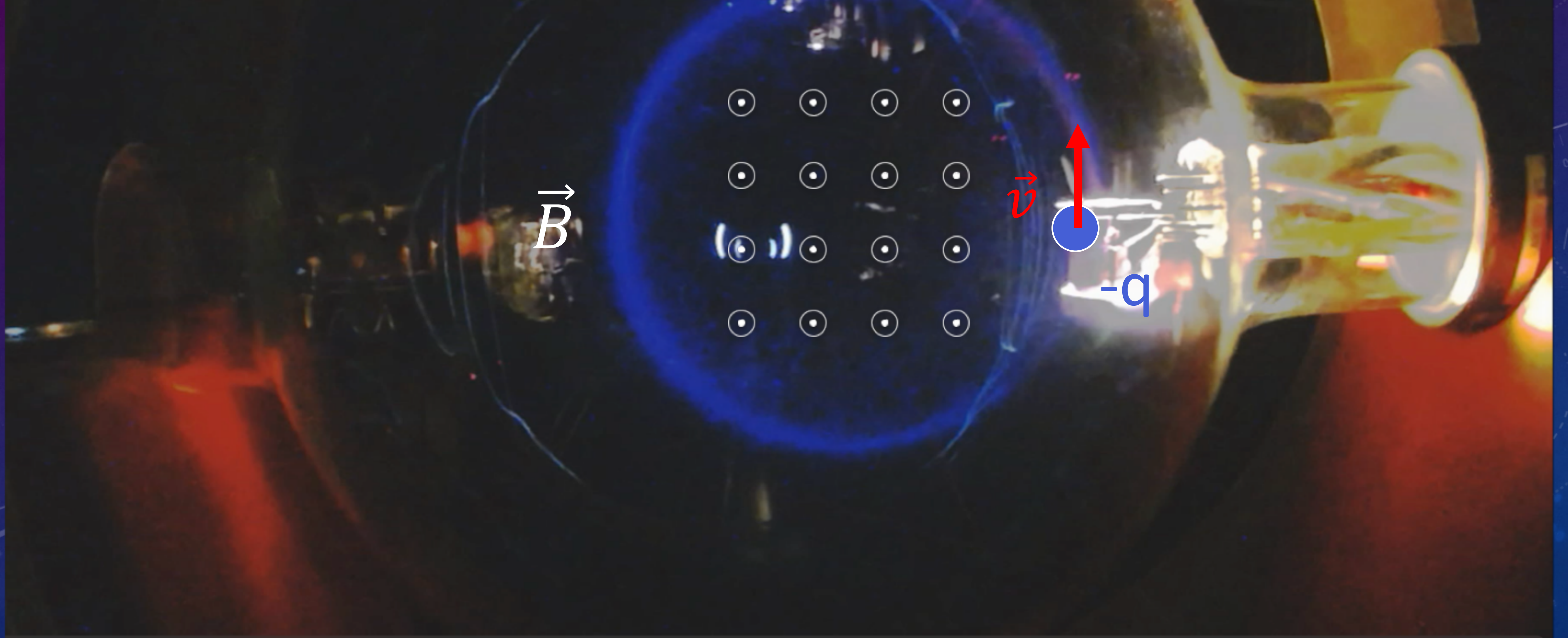
TRIUMF’s cyclotron in construction: world’s largest beam radius of 310 inches



HOW MUCH BIGGER CAN YOU GO?

- It would be great if we could use smaller magnets, re-use magnets
- In fact, it would be great if we could get the beam to trace out exactly the same path, no matter what energy it is. Then you could re-use everything.

What if MAGNETIC FIELD is INCREASED and velocity stays the same?



What if MAGNETIC FIELD is INCREASED and velocity stays the same?

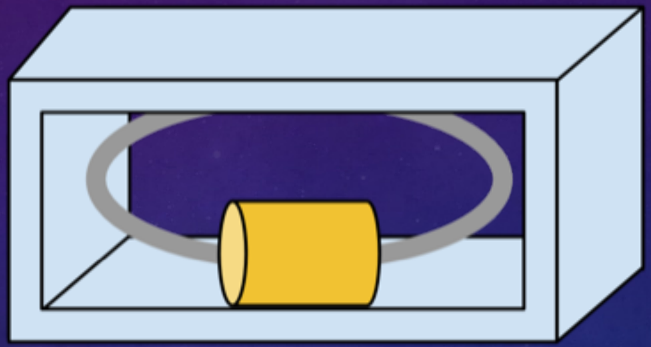
What if MAGNETIC FIELD is INCREASED and velocity stays the same?

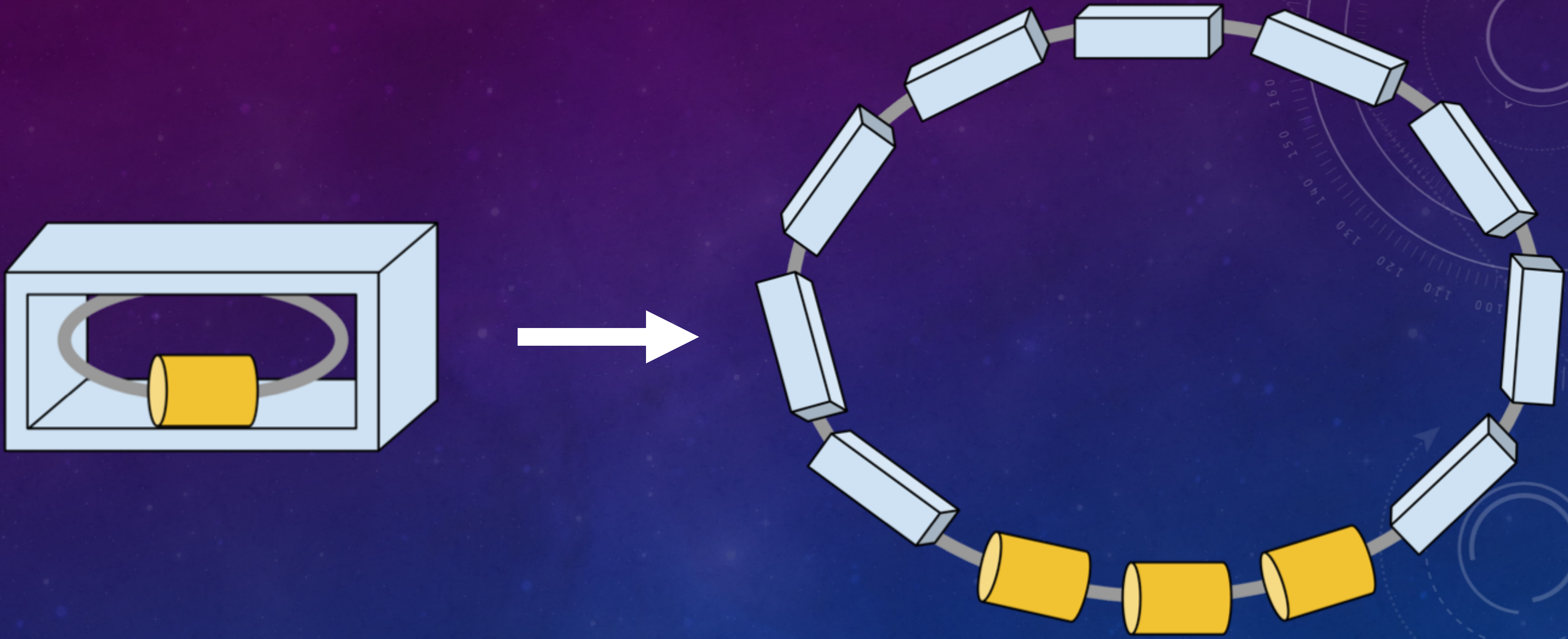
Radius of circle gets smaller

So if we increase velocity (radius bigger)
AND increase magnetic field (radius smaller),
at the same time, in a balanced way...

$$\vec{F} = q\,\vec{v} \times \vec{B}$$

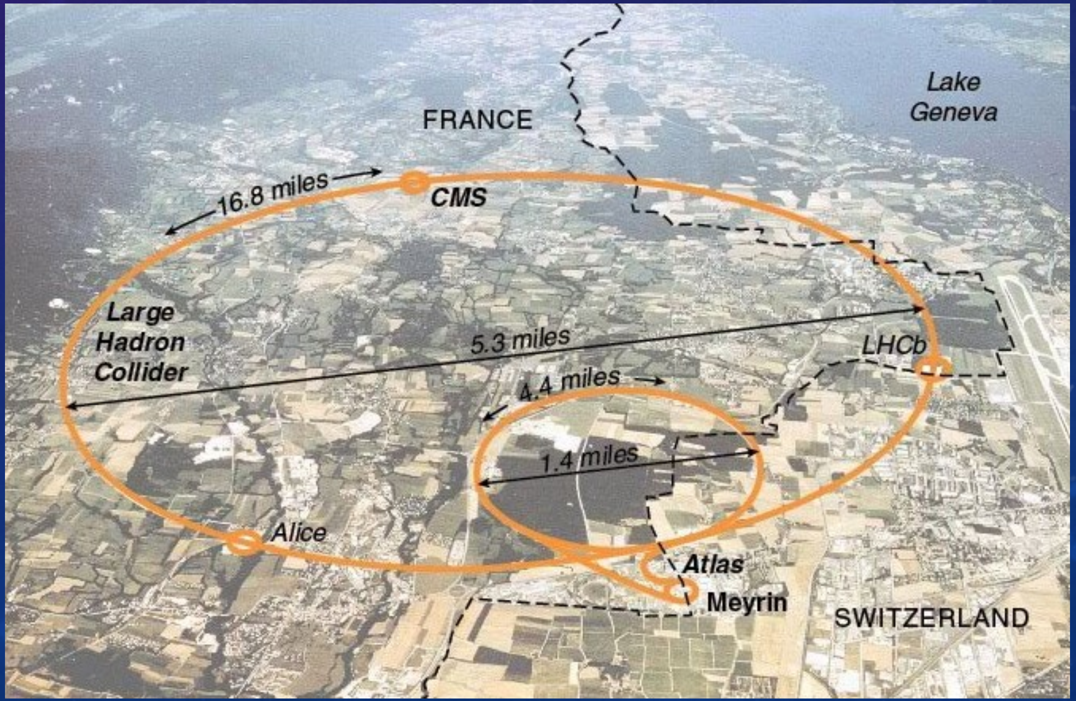
Radius will stay the same!

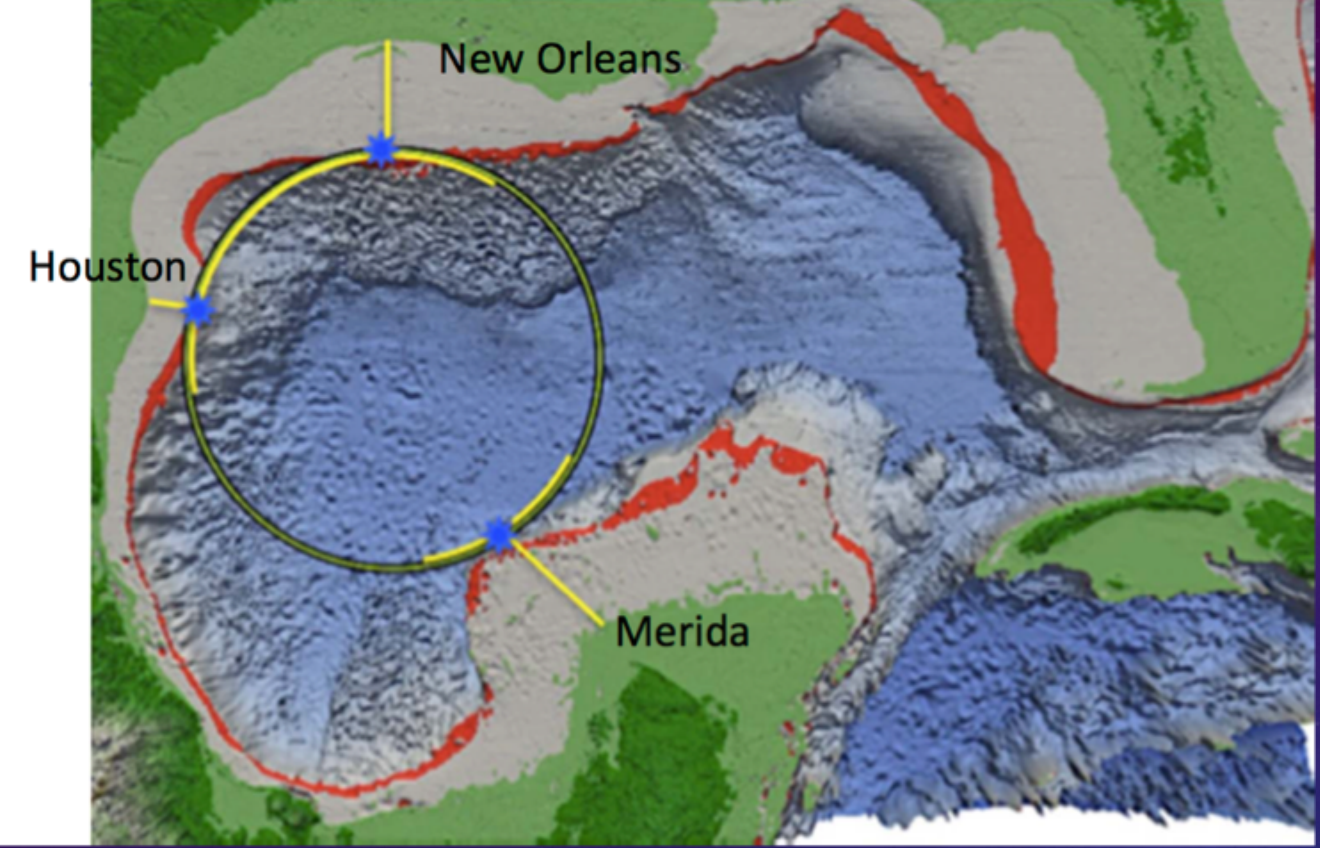




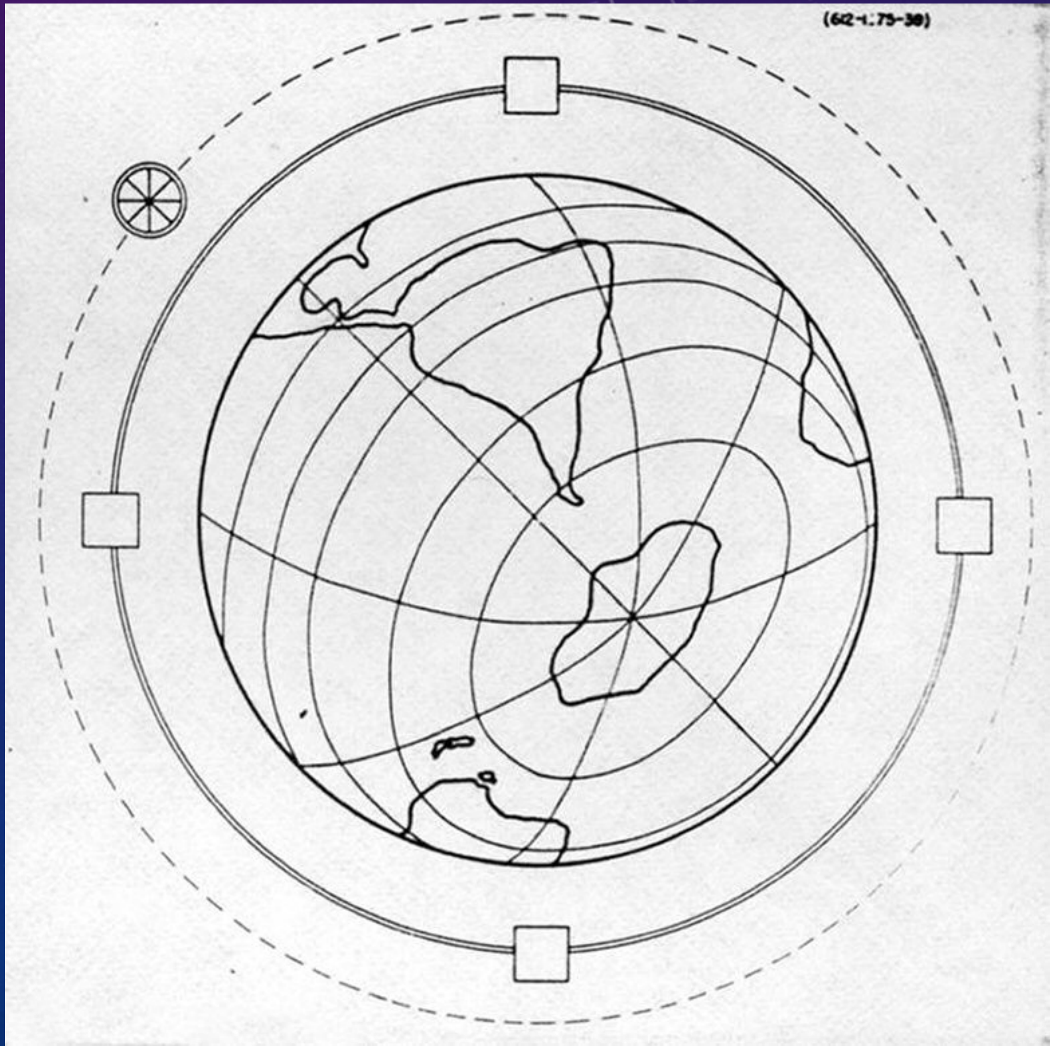
SYNCHROTRON

- Increase the magnetic field as the particles go faster and faster. If done in a synchronized manner, the particles take the same path.
- The highest energy machines are all synchrotrons
- Fermilab's Main Ring and then Tevatron (1983-2011), the LHC at CERN





Special Collections Research Center, University of Chicago Library, from a 1954 talk given by Enrico Fermi

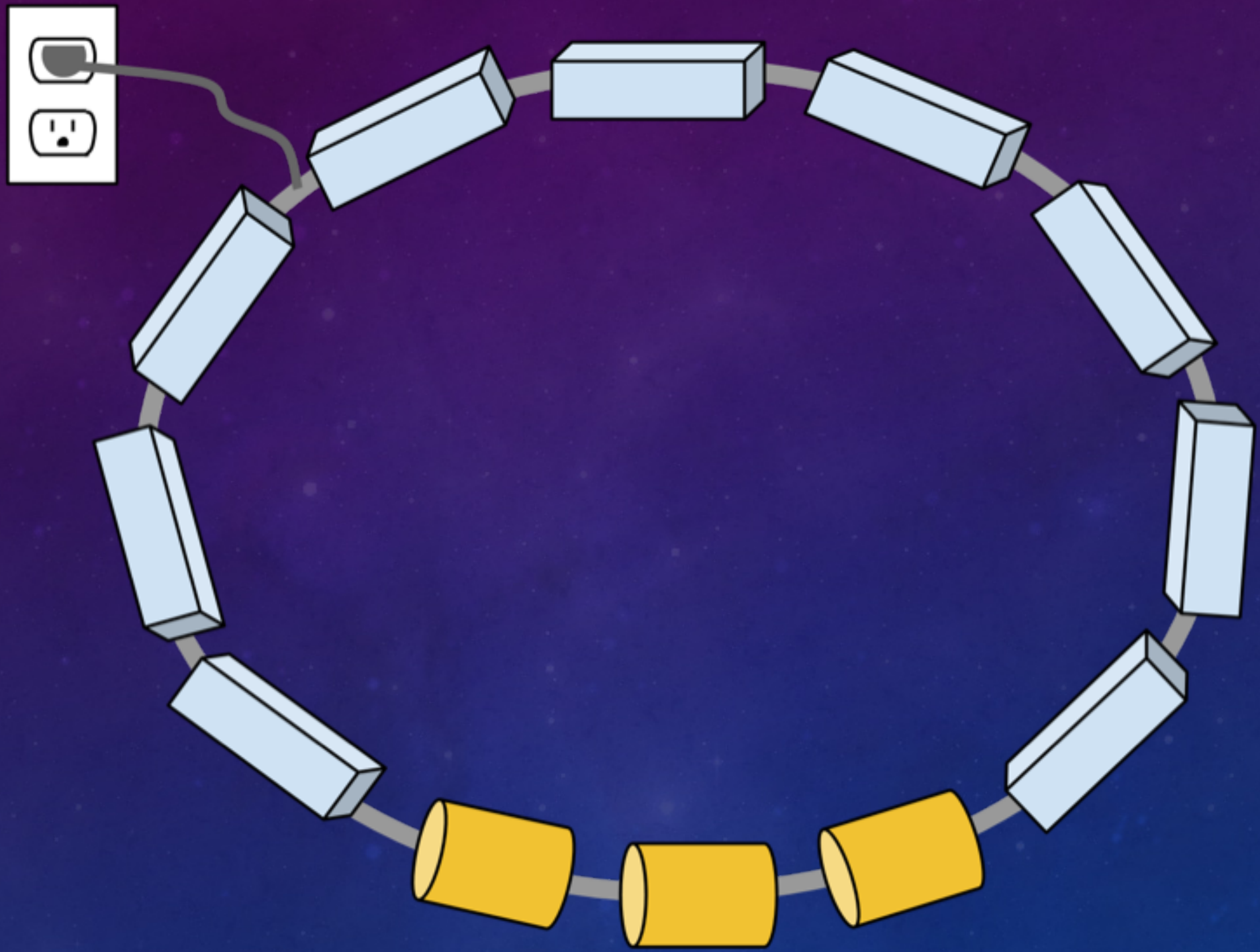


S. Assadi et al, Accelerator Research Lab at Texas A&M University, from a talk given at NAPAC 2016

Theoretical…for now

OTHER PRACTICAL CONCERNS

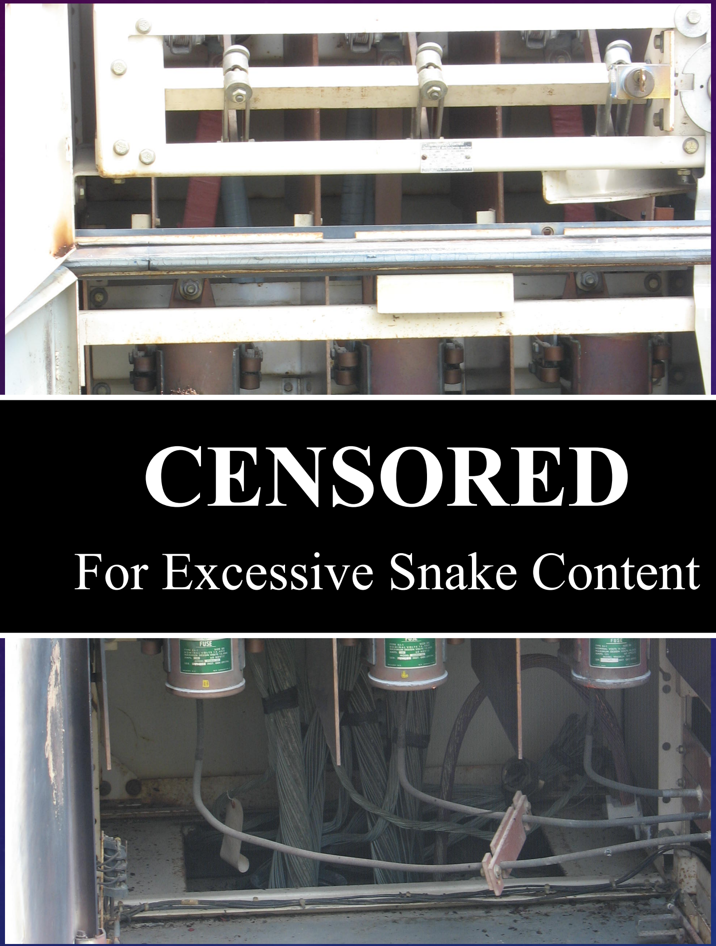
- High power
- Cooling
- Vacuum
- Controls



POWER

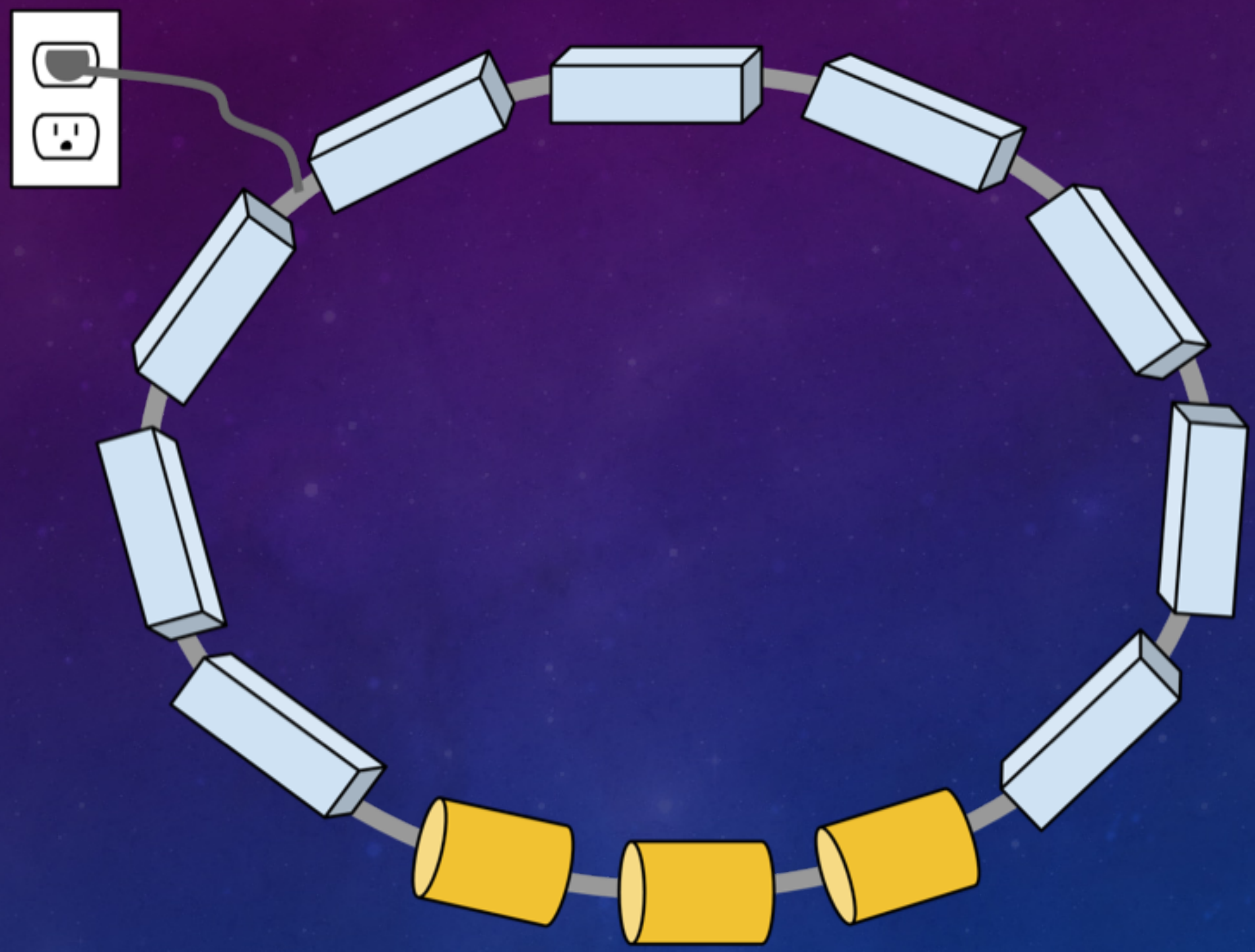
POWER

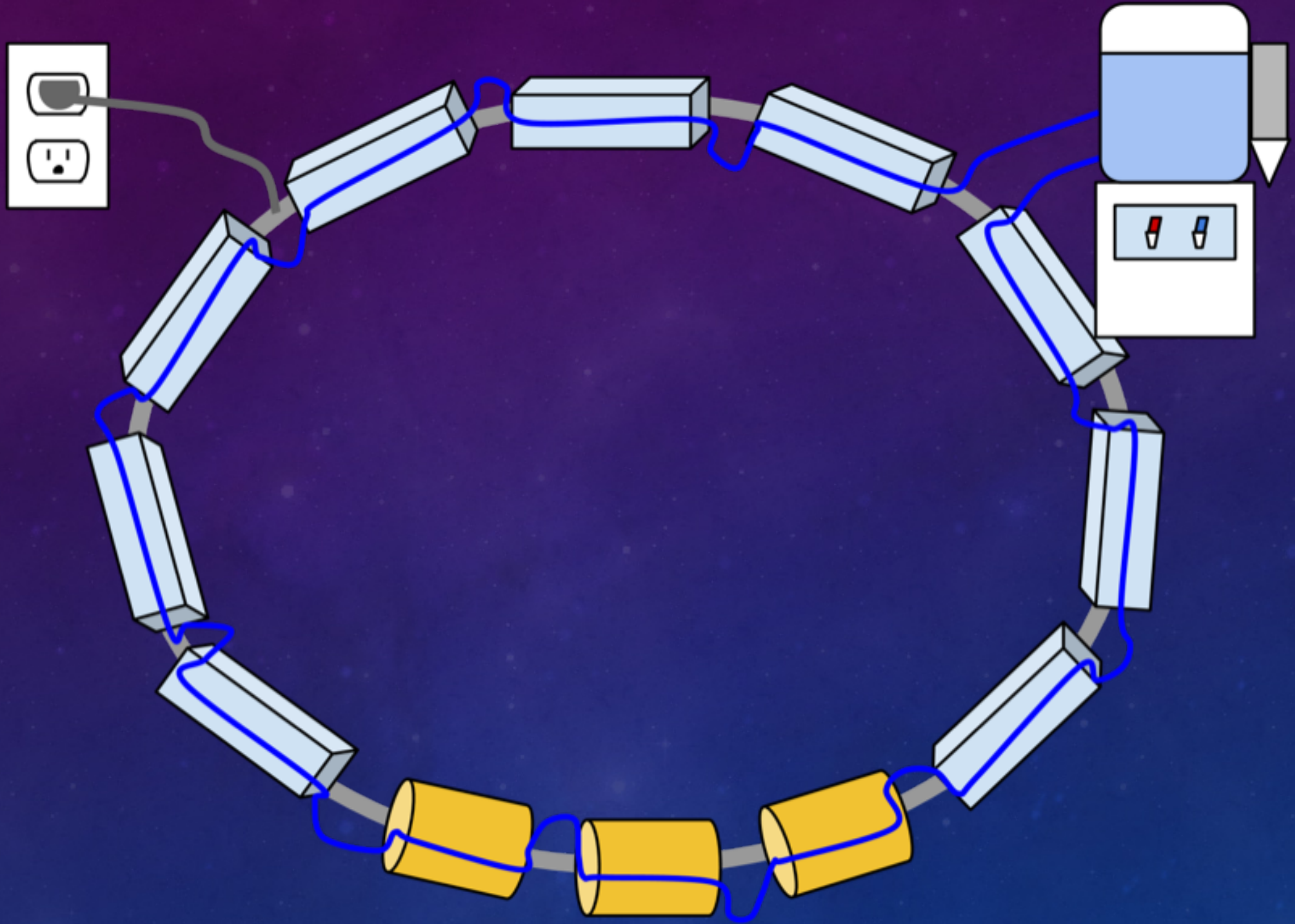
- Everything runs on electricity! LOTS of electricity.
- Contrary to popular belief, we do not make our own electricity—we buy it like everybody else
- Power supplies of various sorts may put out up to 200,000 A (1 A = a toaster!) for high-current applications or 30,000 volts or more for high-voltage applications
- Any interruption to power is debilitating (lightning strikes…water leaks…snakes…)



CENSORED

For Excessive Snake Content

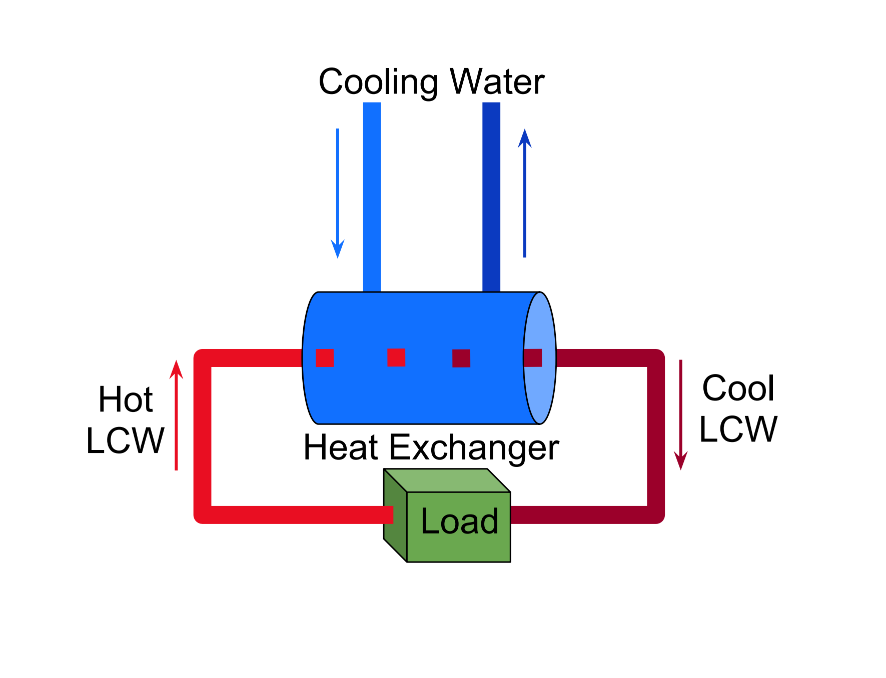


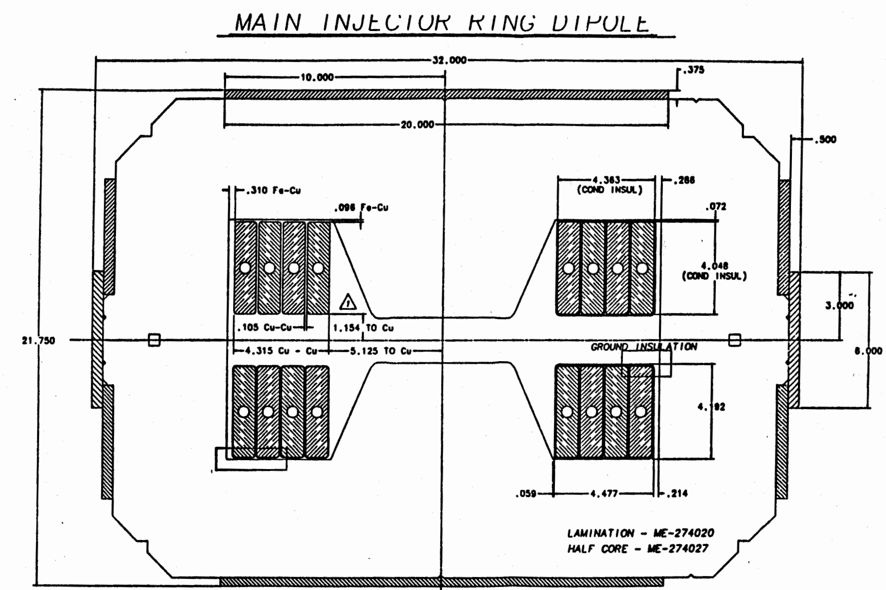


COOLING

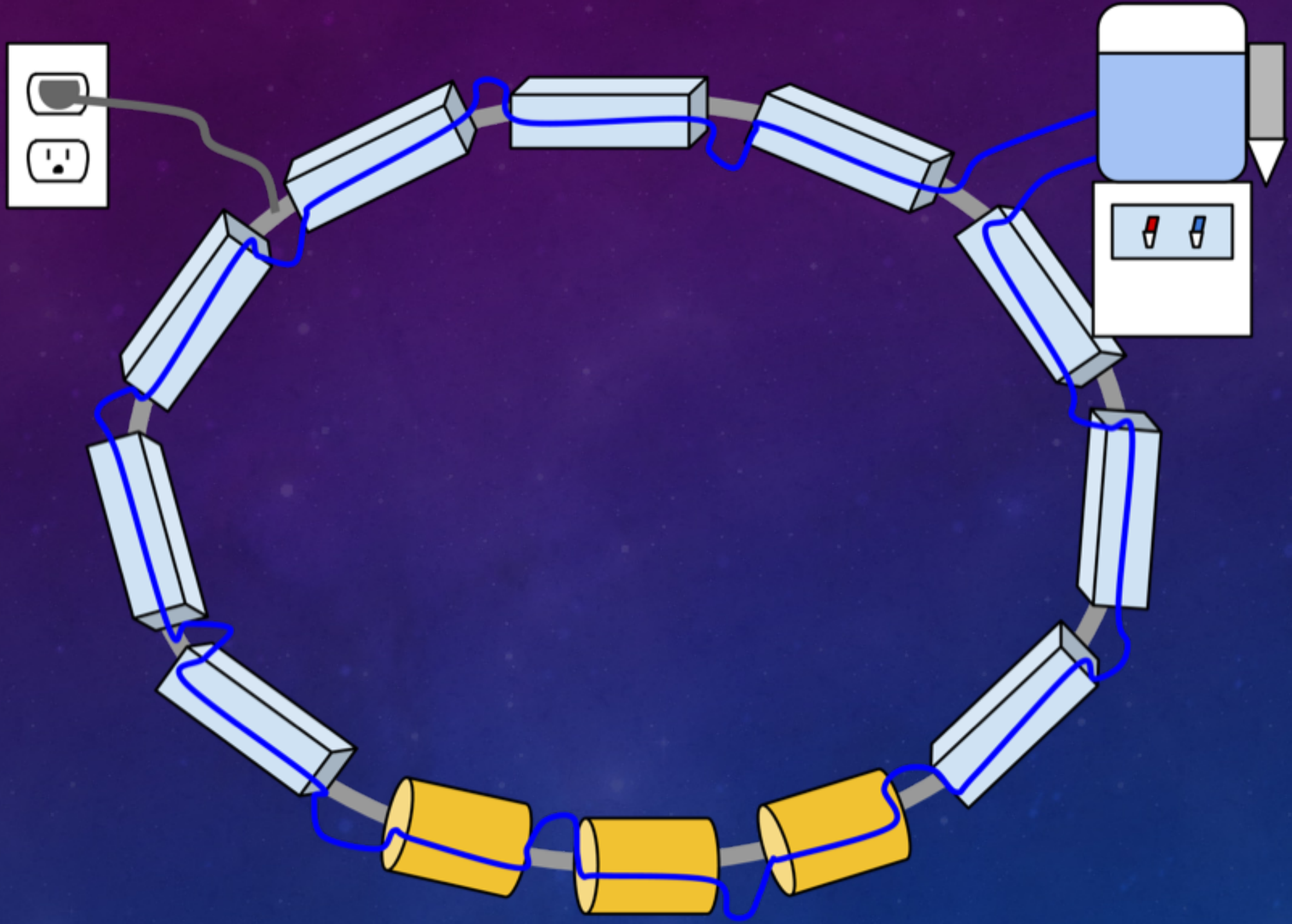
COOLING (LCW)

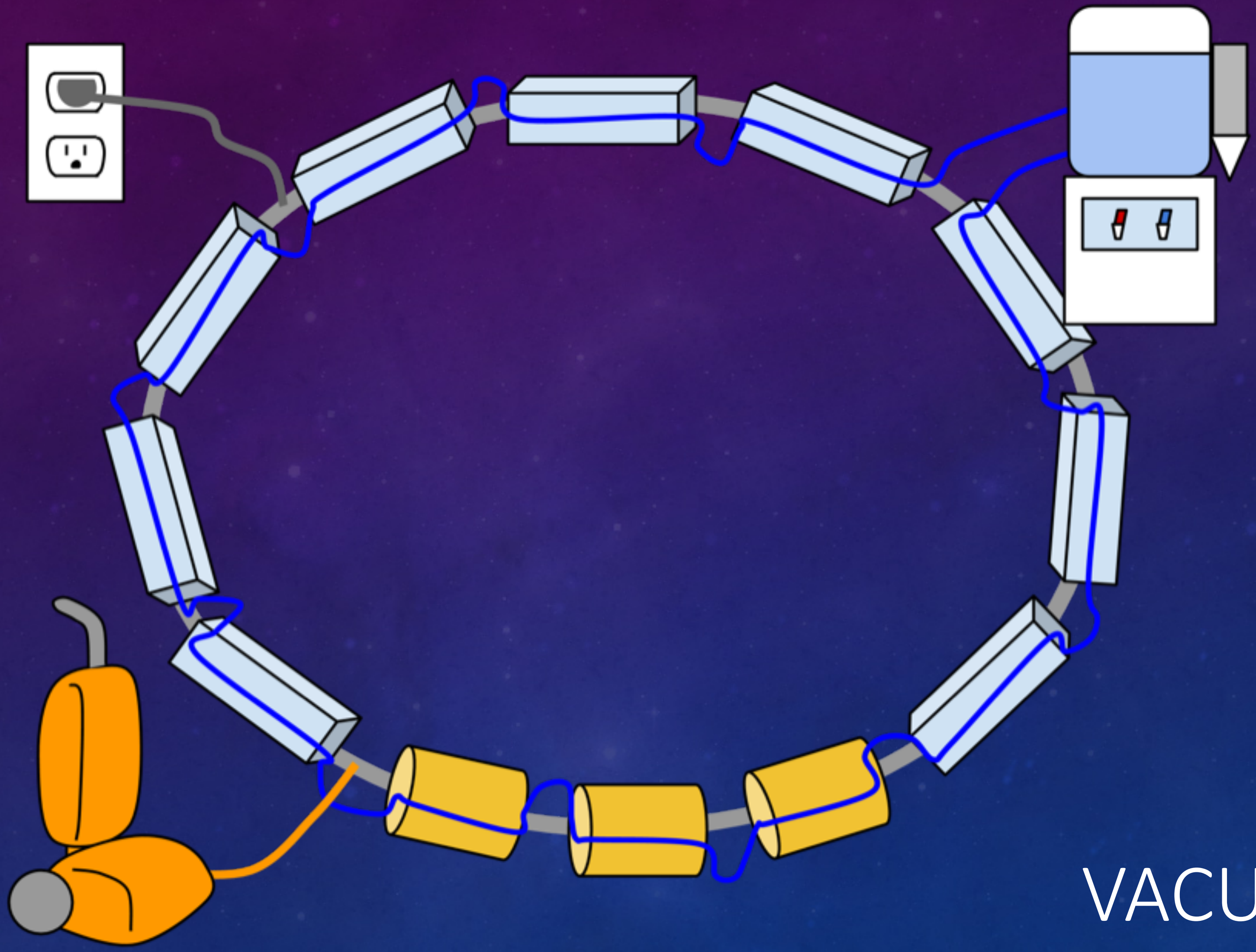
- Power supplies, magnets, RF cavities, and other components get so hot while in use that they often need cooling.
- LCW = Low Conductivity Water
- LCW can be pumped safely through electrical systems for cooling.
- Cooling water carries the heat away and heat exchangers allow us to discharge the heat elsewhere.





Picture by Elliott McCrory

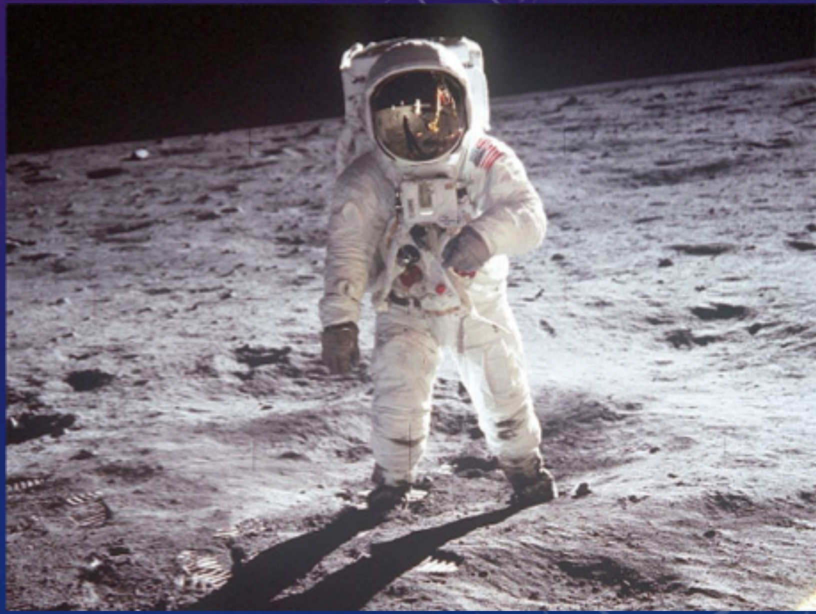


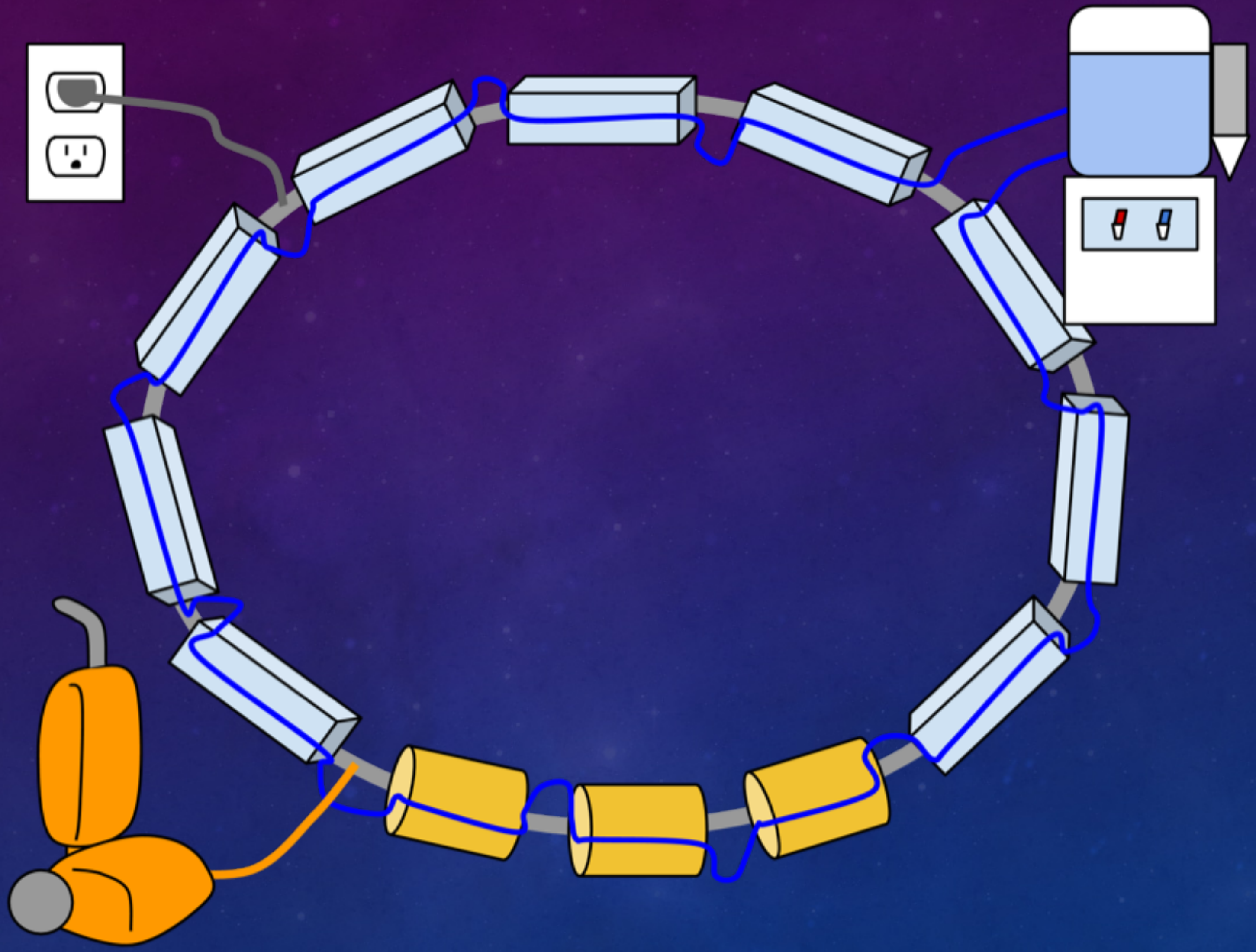


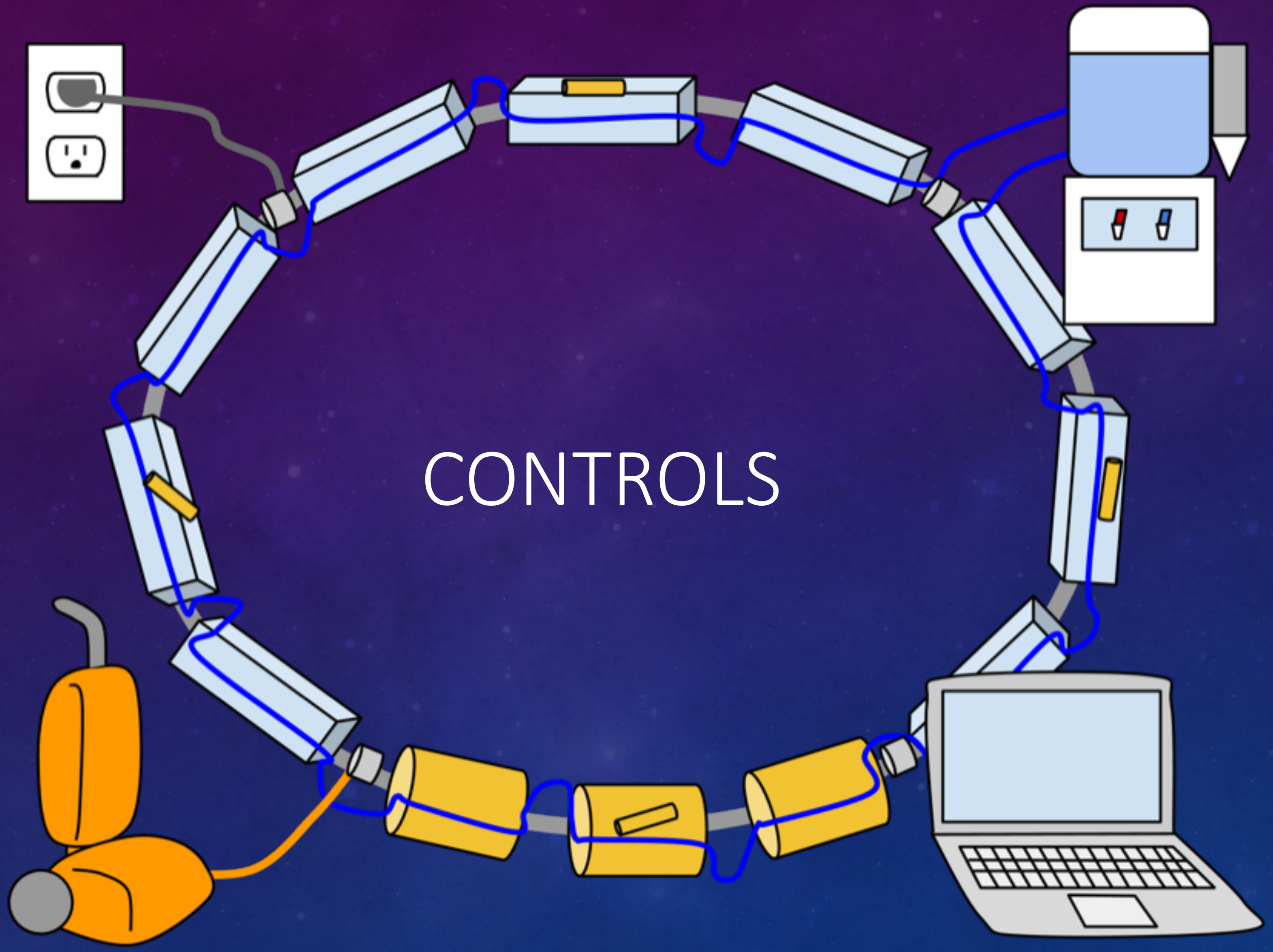
VACUUM

VACUUM

- Empty the beampipe of everything but beam, and maintain that emptiness
- In some cases we pump down to vacuum levels like that in outer space around Earth's moon
- Different kinds of vacuum pumps: roughing, turbo, ion
- Even cryogenics, used in superconducting applications, can provide vacuum improvement: by freezing stray gases solidly to the sides of the beampipe

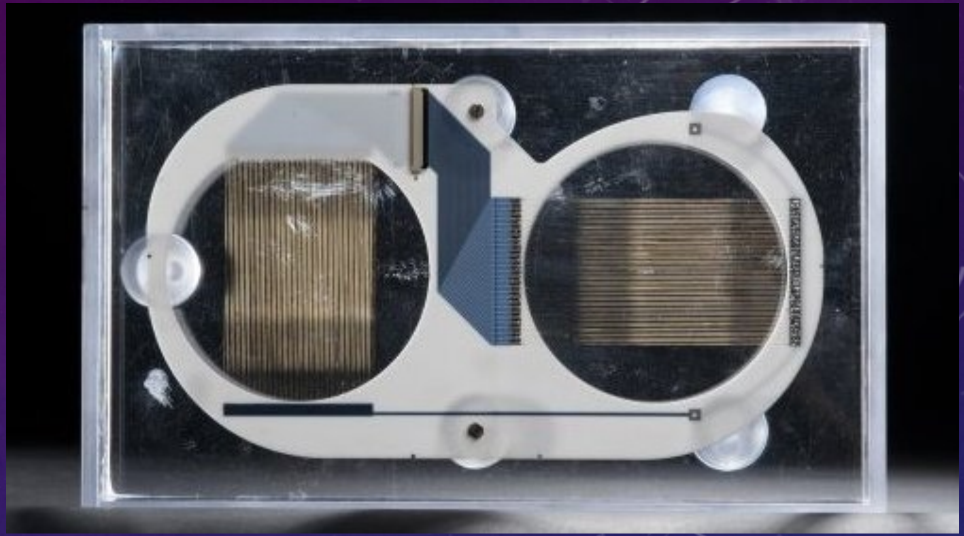




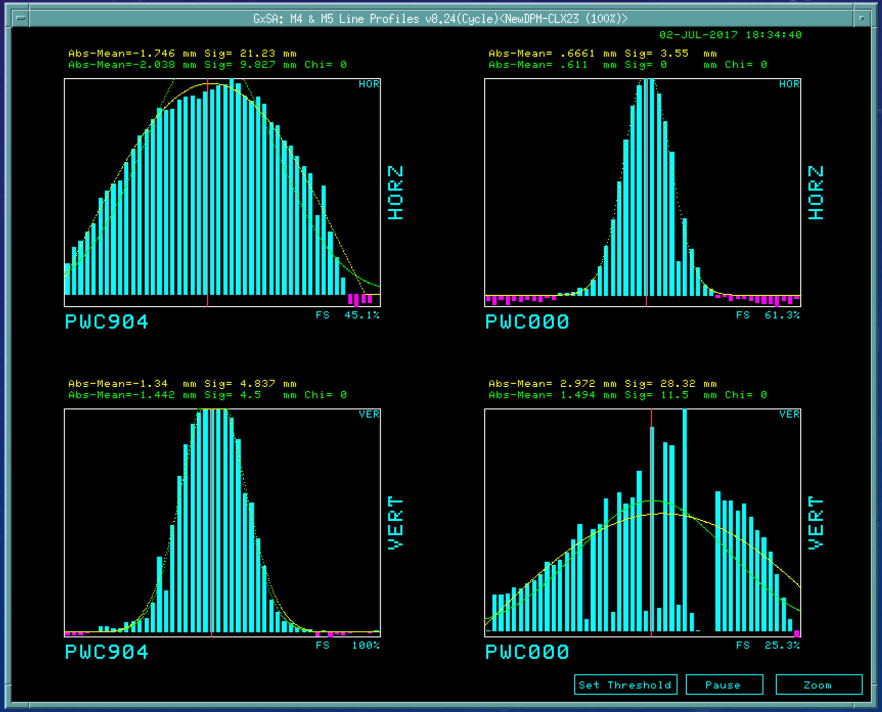


CONTROLS

CONTROLS, DIAGNOSTICS, & INSTRUMENTATION



- A way to see what's going on!
- Feed back information about what's going on with the accelerator components and the beam
- Ways to make changes, corrections, and adjustments
- Lots of clever ways to obtain info about the beam while affecting it as little as possible: lots of science and engineering goes into this
- And detectors are, after all, also a form of beam instrumentation as well

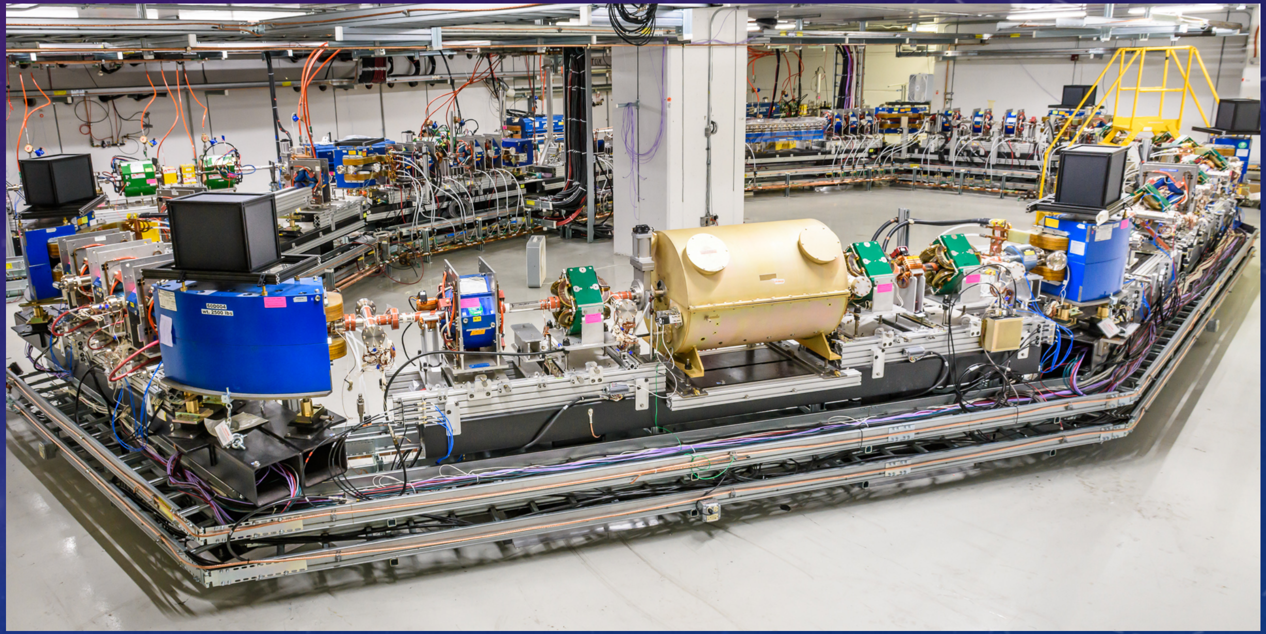


DIFFERENT ACCELERATORS HAVE DIFFERENT USES

- It’s not a strict hierarchy of better or worse, older or newer
- Electrostatic machines have their own uses
- Linacs are the right choice for many applications, like for e- machines
- Cyclotrons are reliable, usually the choice for medical machines
- Pros and Cons, using the right machine for the right reasons/situation

OTHER FERMILAB ACCELERATOR TOPICS FOR FURTHER EXPLORATION

- PIP-II: https://pip2.fnal.gov
- IOTA @ FAST: https://fast.fnal.gov
  - source paper on concept of nonlinear integrable optics (Danilov & Nagaitsev, 2010) https://arxiv.org/pdf/1003.0644.pdf
- Superconducting RF R&D: https://td.fnal.gov/srf-rd/
  - Tech is also interesting from a quantum computing perspective



ACCELERATOR OPERATIONS

- If possible, please try to go on an accelerator tour if you ever get the chance!
- Fermilab tours will usually include the Linac and the Main Control Room, where Fermilab's accelerator operators monitor the beam and the entire accelerator complex 24/7/365.
- I talk more about operator life in my 2015 Fermilab Physics Slam presentation

2015 Physics Slam - Cindy Joe - YouTube

https://www.youtube.com/watch?v=gb1pTjF_sVg ▾

Dec 2, 2015 - Uploaded by Fermilab

Cindy Joe, Accelerator operator at Fermilab, makes her presentation on a day in her life at the 2015 Fermilab ...

WHAT MAKES A GOOD ACCELERATOR OPERATOR?

- Your typical Fermilab operator has a physics bachelor’s or related background, but no higher degree. This is a rare physics job which you can get with only a bachelor’s.
- But more importantly: curiosity and drive to learn, a “tinkering” mindset, dedication, tenacity
- The ability to put ego aside, ask stupid questions, and learn from every opportunity and every person.
- Things don’t always work out in real life as prettily as they do on paper. You can plan it all out, but the beam and the machines will do what they want to do. You need to adjust your expectations and respond to what you see, not what you wish you saw.


Main Control Room
Kimwipes


MI 12


EXIT

QUESTIONS?

- THANK YOU for your attention (and for building an accelerator with me)
- Just touched the tip of the iceberg of topics in both breadth and depth, but I hope I've given you some things to think about and further explore
- cindyjoe@fnal.gov